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Authors
Dedrick, Jason
Gurbaxani, Viijay
Kraemer, Kenneth L.

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Jason Dedrick, Vijay Gurbaxani and Kenneth L. Kraemer
Center for Research on Information Technology and Organizations
University of California, Irvine

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I. INTRODUCTION

The U.S. economy witnessed impressive productivity growth in the second half of the 1990s, resulting in higher living standards for Americans as incomes rose and unemployment fell. There is an emerging consensus that a major source of this surge was corporate investment in information technology (IT)[1], driven by the rapid decline in the prices of IT equipment. In the face of these price declines, companies have had strong economic incentives to substitute IT for other forms of capital and labor. This shift in capital investment helped the economy achieve increased productivity and economic growth while maintaining low inflation.

In mid-2000, capital investment by corporations, and IT capital investment in particular, began to fall sharply, partly due to higher interest rates and slowing economic growth. Moreover, the collapse of many Internet firms had far-reaching impacts. Not only did their own investments in IT disappear, but more established firms felt less pressure to invest in IT in order to respond to competition from these newcomers. This reduction in IT investment has had devastating effects on the IT-producing sector, and may be leading to slower economic and productivity growth in the U.S. economy.

While the decline in market valuation in the technology sector has been unsettling to investors and executives alike, it should not overshadow the fundamental changes that have occurred as a result of firms' investments in IT. In many companies, information technologies are more than a means of enhancing productivity; they facilitate expansion into new markets, and enable the development of new technology-intensive products that can drive revenue and profits. Moreover, notwithstanding the demise of the start-up Internet companies, the returns to IT investment are real, and innovative companies continue to lead the way. These companies are engaging in complementary management practices that enhance the returns to IT investment, discovering and exploiting the efficiencies that the Internet and other networks enable, and setting new standards of competition.

In this paper, we assess the scientific evidence relating IT investment to productivity. We conclude that investments in IT have high average payoffs at both the firm and country level and that those payoffs were evident long before the productivity surge of the late 1990s. We also conclude that while average returns are high, there is a great deal of variance among firms, and that much of the variance can be attributed to investments in organizational assets that are complementary to IT investments.

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[1] Information technology, or IT, refers to computer and telecommunications equipment, software and related services in this and in many of the economic studies. Some define IT more narrowly as computer and/or telecommunications hardware only.

II. INFORMATION TECHNOLOGY AND ECONOMIC PERFORMANCE

> "You can see the computer age everywhere but in the productivity statistics." (Robert Solow, 1987).

> "Despite differences in methodology and data sources, a consensus is building that the remarkable behavior of IT prices provides the key to the surge in economic growth." (Dale Jorgenson, 2001).

For many years, there was considerable question as to whether the IT revolution was paying off in higher productivity. Today, there is now virtually no question that the impact of IT investment on labor productivity is significant and positive. The current debate focuses on whether the move to an IT-intensive networked economy is a fundamental change accompanied by a permanent improvement in the prospects for economic growth, or whether it is a temporary phenomenon, enabled not just by information technologies, but also by the business cycle.

How IT can affect productivity

In order to better understand the debate, it is useful to begin with a discussion of the role of information technology as a factor of production. One approach that economists have used to model the production process inherent in an economy (or industry) is growth accounting. This approach attempts to relate the output of an economy or industry to the inputs based on certain assumptions about the nature of production. Inputs typically accounted for in this approach include labor and capital, including IT capital. A related approach to understanding the output of an economy is production economics, which uses specific functional forms to model the production process.

Clearly, increasing the level of inputs is a source of increasing output. One way is by increasing labor hours, which can increase output, but by definition has no impact on labor productivity. There are three ways of increasing labor productivity. First is by increasing the level of capital applied per unit of labor, a phenomenon called capital deepening. A second source of productivity growth is improvements in the quality of inputs, and labor in particular, as a result of education and training. A third factor is multifactor productivity (MFP) growth, which is the remainder of growth that cannot be accounted for by the first two factors. An increase in MFP means that for a fixed level and quality of inputs, a firm, industry or economy is achieving higher levels of output. An MFP increase implies that production methods have improved or the quality of products enhanced, since that is the only way higher output levels can be achieved from the same inputs.

Improvements in production processes can occur for a variety of reasons. Research and development on product and process technologies can account for increases in MFP. There is no question that there have been very rapid improvements in MFP in the IT industry, particularly in computer hardware and components. This increase accounts for a significant part of the gains in MFP at the level of the economy. For instance, different economists estimate that anywhere from 25% to 100% of the MFP acceleration of the late 1990s was accounted for by the IT-producing and durable goods sectors. A critical question is whether there have been similar gains in MFP outside the IT industry and if so, whether those gains can be attributed to investment in IT capital. Has the use of IT allowed industries to achieve superior production methods that were previously unavailable? Put differently, are there spillovers from IT-producing industries to IT-using industries?

To answer these questions, it is essential to look at the role of IT capital in organizations. Much of the debate among economists has addressed these issues at the aggregate level of the economy. Yet, the decision makers who choose to invest in IT are managers in organizations who use firm-level investment criteria. While productivity is certainly one often-used criterion, managers also use measures such as market share, margins, product variety, quality and profits as justifications for investment in IT systems.

Role of IT in organizations

In order to understand the overall impact of IT at the organization level, it is useful to begin by thinking about the qualitative impacts of introducing IT into an organization's production processes. Past research has distinguished between using IT to automate processes, to provide better information, and to transform entire processes (Zuboff (1988). The impact of automation is primarily the direct substitution of capital for labor, consistent with capital deepening. For example, a cashier at a retail chain store using a computer based information system such as a scanner can process a transaction in less time. The impact of improved information is that it allows workers and managers to make more effective decisions. To stay with the above example, information provided by the store-based system allows the firm to make better inventory decisions. Transformation impacts occur when a firm re-engineers a process to achieve significantly higher levels of productivity. In our example, the firm may redesign their supply chain using a supply chain management system, of which the store system is a key element.

One key difference between IT capital and other forms of capital is the dual roles that IT can play in an organization. First, like other types of capital, IT can be used directly as a production technology, as in the case of a bank's transaction processing system. However, research suggests IT has its greatest impact in its second role as a coordination technology (Bresnahan, 1997; Malone, Yates and Benjamin 1987, Gurbaxani and Whang 1991). In this literature, IT is viewed as an especially potent technology that has a significant impact on the costs of coordinating economic activity both within and between organizations. Research in this arena suggests that the unique value of IT is that it enables fundamental changes in business processes and organizational structures that can enhance both labor productivity and MFP.

A comprehensive review of the payoffs from IT investment must examine the returns to this investment at aggregate levels such as the economy and disaggregate levels such as the firm since the nature of the payoffs at these two levels is quite different. Moreover, the aggregation of firm-level results may lead to a misconception of the structure of payoffs since aggregation can mask firm-specific factors such as the quality of management, and the fact that returns to one firm may mean lower returns to its competitor. In general however, the mechanisms by which the payoffs are realized are similar in that potential increases in labor productivity and MFP are at the heart of the gains that accrue both to firms and to the economy.

In order to understand whether IT investment results in greater productivity, it is important to look systematically at the research on the returns from IT investments. We examine the research as a basis for understanding the nature, extent and limitations of payoffs from IT investments. We review the evidence provided by numerous systematic, empirical studies at the firm and country levels.

III. FIRM-LEVEL RESEARCH

While the productivity paradox as originally framed focused on aggregate country-level productivity statistics, most IT investments are made by organizations, mostly firms, who are interested in their own return on investment, not that of the country as a whole. Knowing that IT investment improves aggregate productivity does not imply that firms, even on average, enjoy similar benefits. In fact, there may be significant social benefits from IT investments that enhance aggregate productivity and increase consumer welfare but are not captured by the firms making those investments. So it is of great concern to business executives whether their IT investments are paying off at the level of the firm.

IT and firm-level productivity

Motivated by the productivity paradox, many firm-level studies were launched in the 1980s and 1990s. Early studies were unable to show that IT investments led to payoffs, in most cases because of inadequate data on IT investments and small sample sizes.[2] Most discouraging were several studies of service firms, such as banks and insurance firms, which showed weak or non-existent links between IT and productivity, but where output measurement is notoriously difficult.[3] Studies of manufacturing firms showed higher returns on IT investment, partly because it is easier to measure the output of manufacturing and adjust for improvements in quality.[4] These studies began to highlight the importance of the accurate measurement of outputs, particularly in the technology-intensive service industries where the largest investments in IT capital were being made.

Starting around 1993, more rigorous studies with larger samples were being reported at the firm level. These studies involved large U.S. corporations, using data on IT capital investment from market research firms and from surveys of chief information officers and other executives, coupled with financial data from reliable sources. The researchers used

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[2] See Brynjolfsson and Yang (1996) and Hitt and Brynjolfsson (2000) for extensive literature reviews on IT and productivity.
[3] Service sector studies include Strassmann (1990), Franke (1987), Harris & Katz (1991), and Alpar & Kim (1991).
[4] Manufacturing sector studies include Weill (1992), Loveman (1994), and Barua et al. (1995).

econometric techniques that relate firm output (measured as value added) to a set of inputs including labor hours, non-IT capital stock and IT capital stock, and measure the marginal product or output elasticity of IT capital.[5]

Each of the major studies found that IT investments contribute to firm productivity, and show higher gross marginal returns than non-IT investments. The fact that these researchers found a strong relationship between IT capital and productivity that was not evident in earlier studies may partly reflect the fact that the data is more recent and that over time firms were learning to apply IT capital more productively. They may also simply reflect better data sets and analytical tools that make it possible to isolate and measure the true impacts of IT investment.

Most of the studies also found that IT investments were associated with higher marginal product than other capital investments. These are translated into "excess returns" by some authors, who point out that in theory, all investments should pay the same risk-adjusted return at the margin. These returns do need to be adjusted to account for the high rate of obsolescence of IT capital, so that the net returns are much lower. However, Brynjolfsson and Hitt (1996) and Lichtenberg (1995) found that after subtracting standard estimates of the cost of IT capital of up to 42% per year from the gross returns, the net returns from IT were still higher than those of non-IT investments. They argue that these higher returns are due, in part, to complementary investments that firms make in organizational assets, that are not properly accounted for as investments in a firm's financial statements.

In addition to these U.S. studies, a few other studies have been conducted on firms in other countries. Greenan et al. (2001) analyze data on French firms' IT investment and productivity and come to results consistent with the findings of Brynjolfsson, Hitt, and Lichtenberg. By contrast, Lal (2001) does not find a relationship between IT investment and productivity in Indian garment makers. This is consistent with the cross-country studies (Dewan and Kraemer, 2000; Pohjola, 2001) that find a strong relationship between IT and productivity in developed countries, but not in developing countries. With low unit costs of labor and higher capital costs, it is not surprising that there are fewer opportunities for capital-labor substitution in developing countries. Also, Lal's sample included many small and medium-sized firms, a group not included in most U.S. studies.

More recently, Brynjolfsson and Hitt (2000) have found that payoffs to IT investment occur not just in labor productivity but also in MFP growth, and that the impact on MFP growth is maximized after a lag of four to seven years. Gilchrist, Gurbaxani and Town (2001), using the same dataset, focus on the manufacturing companies in the sample and show that IT has a substantial and contemporaneous impact on labor productivity and on MFP growth in the durable goods sector, which exceeds the impact that would be predicted by its factor share. They find that in the non-durable goods sector, the returns accrue primarily to labor productivity via capital deepening, and are consistent with IT's factor share. Moreover, these returns are correlated with decentralized computing architectures, suggesting that the diffusion and networking of computing throughout the organization contributes substantially to the payoff.

[5] The output elasticity of IT is the increase in value added associated with 1% increase in IT investment.

This recent research highlights interesting questions that remain unresolved regarding the payoffs from investments in IT capital. First, it is not well understood why firms in different industries accrue different payoffs. For example, it would be valuable to identify the specific characteristics of durable goods firms that enable them to achieve higher returns relative to non-durable manufacturing firms. Second, a better understanding of the timing of the payoff from investments in IT capital is also needed. Clearly, a firm's many individual investments in specific systems will have different periods over which the payoffs will be realized. Some systems will realize immediate payoffs, while others will realize payoffs after a lag. The duration over which the payoffs will be realized will also vary. Some will have short-term impact and others will have a longer-term impact. This understanding will go a long way to resolving the debate on whether the impact of these investments is contemporaneous or occurs in the future.

Variance among individual firms

The preponderance of evidence points to positive and significant returns to IT investment among firms. Clearly, higher levels of IT investment are associated with higher levels of productivity across a large sample of companies, and this has been true since the mid-1980s at least. However, looking at a scatter plot of IT investment and productivity, as Brynjolfsson and Hitt present in several of their papers, one is struck by how widely scattered the actual data points are around the trend line. This leads to the next major finding in the firm-level data.

The productivity impacts of IT investments vary widely among different companies.[6] In other words, some firms use IT more productively than others. Brynjolfsson and Hitt (1995) estimate that these "firm effects" may account for as much as half of the productivity benefits attributed to IT investment in their earlier work, but state that the elasticity of IT remains positive and significant even after firm effects are taken into account. Still, this raises the question of what causes these firm effects.

Two factors stand out. First, there are firm idiosyncrasies such as market position, rigidities in cost structures (e.g., labor contracts), brand recognition, or the vision and leadership abilities of key executives, which affect a firm's strategic options and therefore its ability to reap the benefits of IT investment. These can change over time, but are not easily manipulated by management in the short run.

Second, there are specific features of organizational structure, strategy, and management practices that can be compared systematically across companies. These variables can be more directly affected by the management of any firm, through restructuring, changing incentives, revising processes, or upgrading employee training.

[6] The variance of returns to IT capital is larger than the variance of returns to non-IT capital.

Impact of business practices on value of IT investments

Management practices and complementary investments explain part of the variation in IT payoffs. Various studies at the firm level show that the value of IT investments is substantially impacted by the structure and business practices of the firms making the investment. For instance, Brynjolfsson and Hitt (2000) and Bresnahan et.al. (2001) show that firms with a cluster of management practices (which they call organizational capital) including decentralized decision-making, along with high levels of IT investments, outperform all others. Meanwhile firms with traditional centralized organizations and high IT investments actually do worse than similar organizations who invest less in IT. Their studies and others (e.g., Tallon, et.al., 2000) found that management practices such as aligning IT with business strategy, employee involvement, total quality management and business process redesign, enhance IT returns.

Black and Lynch (1997) studied the impacts of workplace practices, IT capital, and human capital development on productivity. They found that what affected productivity was not the presence or absence of a particular management practice, such as total quality management, but the way in which the practice was implemented. Particularly important was employee involvement, for instance the proportion of workers involved in regular decision making in a plant. They also found that a higher proportion of non-managerial employees using computers was associated with greater productivity.

While the evidence shows the benefits of certain classes of management practices, these can be difficult to translate into specific actions for individual companies. It is logical that executives and managers can improve the performance of their IT investments by combining these investments with proven complementary managerial practices. However, the research evidence is limited as to specific links between management practices and productivity. In particular, understanding the relationship between firm-specific factors and management practices is critical and by definition cannot be addressed in large sample studies. For instance, the fact that decentralized firms earn higher returns to their IT investments than centralized firms on average is not sufficient to advise a particular firm to make a radical change in organizational structure. Given a firm's idiosyncratic characteristics, a centralized structure might be most appropriate.

IT and financial performance

There is mixed evidence at the firm level as to the impacts of IT capital on financial performance measures such as profitability or market value. From the management point of view, the contribution of IT capital to financial performance would be of great interest. Here the evidence is less clear, partly because the linkage is less direct. While IT investments can directly affect a firm's output and many operational indicators (e.g., inventory turnover, plant productivity, product quality), a firm's financial performance is determined by a wider range of strategic and competitive factors that go beyond its productivity.

Early efforts to relate IT investment to financial performance have had mixed results. Brynjolfsson and Yang (1997) found that a dollar of computer capital was associated with between $5 and $20 (depending on assumptions in the models) in additional market capitalization for public companies, pointing to a link between IT and financial valuation. This does not mean that simply adding IT increases market capitalization; instead the authors interpret these findings as evidence of important but unmeasured complementary organizational practices, or intangible assets, that are not included in the accounting of firm-level investment. Brynjolfsson, Hitt and Yang (2000) find that organizational capital (i.e. the cluster of complementary practices mentioned previously) by itself increases market valuation and decreases the amount attributable to IT by itself. They also find that market valuation effects are greatest for firms that have both high IT and high organizational capital, pointing again to the complementarity of the two factors.

So far, studies have failed to identify a relationship between IT investment and firm profitability. Hitt and Brynjolfsson (1996) show that while IT investment affects productivity and creates consumer surplus, it does not necessarily improve profitability. They propose that the productivity benefits associated with IT use may be passed on to consumers through lower prices and not lead to greater profitability. On the other hand, it is possible and even likely that IT investments do actually affect profitability, but the modeling techniques and datasets used in these studies are unable to measure the impacts. As models are developed that are able to control for more of the additional factors that affect profitability, they may reveal a relationship between IT investment and financial performance.

IT and labor

Firm studies have shown that IT capital has been a net substitute for labor, as the use of IT allows firms to reduce headcounts or to grow output faster than employment.[7] In addition, studies have identified strong evidence of a shift in demand toward higher skill levels related to the introduction and diffusion of IT. This process is referred to as skill-biased technical change.

IT use is associated with a shift toward workers with higher skill levels, and these workers earn higher wages on average. Comparing industry sectors, Autor et. al. (1998) found that the rate of skill upgrading has been most rapid in industries that are the most intensive users of computers. Looking at the U.S. labor force, Krueger (1993) found that workers who used computers earned 10-15% more than non-users. Similar results have been found in studies of other developed countries.[8] Dinardo and Pischke (1997) offer a competing perspective, finding not just a strong correlation between wages and computer use in German data, but equally robust correlations for workers who use pencils, pens, calculators or telephones. They argue that these findings cast doubt on the interpretation that the wage

[7] For example, Dewan and Min, 1997

[8] See Chennells and Van Reenen (1999) for a broad survey of survey of research in this area.

differential reflects returns to computer use, but reflect in fact, the nature of the work, and the implied skill sets of the workers. Moreover, as Chennells and Van Reenen (1999) point out, there is much evidence that workers with the best skills are given the best technology to use.

It is also important to identify what mechanism might account for the relationship between computer use and skill level. Bresnahan (1999) argues that the process of skill upgrading is due to organizational changes related to computerization, rather than individual use of computers. In particular, computer systems enable work to be shared between a worker and the system, with many standard and repetitive tasks now conducted by the system, but many of the higher cognitive tasks still conducted by the worker. Correspondingly, much clerical work is conducted by automated systems today, changing the nature of clerical work to focus on more complex situations, and those that require human intervention. In the case of highly educated workers, work is more supported rather than automated by computers. In this view, organizational computing systems have been a substitute for low- and middle-skill white collar workers while creating more demand for high-skill workers. This process could explain the higher skill levels and higher wage rates associated with IT use.

In an empirical study, Bresnahan et al. (2001) test the relationship between IT use, organizational change and skill levels at the firm level. They find that the use of IT, along with complementary workplace reorganization and a higher rate of introduction of new products and services, all tend to result in greater use of high-skilled labor. They also find that organizational changes accompanied by technology change may have a greater impact on skill levels than technology change alone. These findings are consistent with the view that IT-enabled organizational changes are responsible for the shift toward higher-skilled workers.

Implications of "excess returns" findings

The results of these studies have sometimes been taken to imply that firms are systematically under investing in IT, given the high marginal returns to such investments. This appears to contradict basic microeconomic theory, which claims that firms will invest up until the point that marginal returns on all investments are equal. If firms are earning higher rates of returns on IT investments than other investments, why don't they raise their level of spending? Are managers acting irrationally, foregoing highly profitable investments?

Some answers have been proposed to this question, and others will be suggested here, but first of all we would warn that claims of systematic under investment in IT should be viewed cautiously. First, as Brynjolfsson and Hitt (2000) point out, the true cost of such investments may be underestimated. All studies include the direct investment in computer hardware, others attempt to include labor, software and services but it is difficult to estimate these with a high degree of precision. Importantly, they do not include the costs of complementary investments such as training and process reengineering that can be much larger than the actual direct investment in IT. If these costs are included on the investment side of the equation, the returns might look much more modest. Moreover, it should be kept in mind that the high rates of depreciation for IT investments mean that *net* returns on investment are much lower than gross returns, and taking into account the large standard deviations in the payoffs documented by many studies, it is possible that the net returns to IT investments are in line with non-IT investments. Note of course, that there are some shortcomings in the measurement of output as well, particularly in the measurement of quality improvements in products and services, and in the measurement of output itself in many industry sectors.

Given all of these caveats, it is still possible that IT investment does show higher than normal returns. There are several reasons that this could be so:

- IT investment might be riskier than other investment. This would argue that returns need to be higher to compensate for the additional risk. As a newer, continuously evolving and complex technology, there is less available experience to guide the management of these investments. This risk is manifested in the frequent time and cost overruns and sometimes spectacular failures observed in many IT projects. Moreover, there may be IT projects that are successfully implemented at a technical level, but the payoff is not realized. Managers whose jobs may be at risk in the case of failure but do not share materially in the gains from successful implementation are likely to be cautious about investing in complex IT projects.
- There might be adjustment costs. It is difficult and costly for firms to introduce new IT innovations. With decreasing prices for IT, the optimal level of IT investment and capital stock increases in steady state. However, firms face real costs and delays due to the duration of software development, retirement of older systems and change in practices that suggest that firms might not achieve these optimal levels in the short run.
- There might be gains for consumers but not profit gains.[9] If productivity gains from IT are passed on to consumers in a highly competitive market, then the incentive to invest in IT is decreased, in spite of potential productivity effects. Yet, if some firms in an industry invest and produce more attractive products for consumers, other firms will be at a competitive disadvantage if they do not invest. So the incentive to invest in IT depends on how responsive a firm's customers are to output prices and quality.
- IT investment might be a strategic necessity but not a competitive advantage. Clemons (1991) argues that IT has become a "strategic necessity," but not a source of competitive advantage, as IT investments do not necessarily create market entry barriers or other sources of sustained competitive advantage. If so, early investors will only experience temporary gains from their investment, and follower firms may not show any measured gains. Rather, they may simply be doing enough to hold on to their present positions or simply survive. In competitive markets, there may be little variation in the profitability data, as firms that fail to invest may simply disappear and survivors may have very similar levels of profitability

It is therefore difficult to conclude that the "excess returns" found in firm-level studies imply that firms are systematically under investing in IT, or that managers are acting

[9] There is substantial research on the demand for IT and the implied gains to consumer surplus that is beyond the scope of this paper. For example, see Bresnahan (1986) and Brynjolfsson (1996).

irrationally. Firms invest when the net return is sufficient to cover the risk-adjusted cost of capital. Given the various measurement problems, questions about the appropriate depreciation rate for IT investments, the level of risk involved in IT investments, the lack of a strong linkage between IT and profitability, and the fact that firms can only absorb new technologies at a certain rate, it is likely that firms are acting rationally and not systematically under investing in IT. Finally, the fact that firms have dramatically increased their IT investments in recent years so that IT accounts for an ever larger share of total investment suggests that managers have recognized the value of IT capital and have reacted accordingly.

Summary of firm-level research

While earlier studies showed mixed results, since the mid-1990s, nearly all major studies have shown positive and significant returns to IT investments. An important point is that the data utilized in the studies run from the late 1980s to the mid-1990s, before the Internet boom and before the advent of the so-called New Economy. As such, the research shows that the issue of whether firms benefit from their IT investments can be separated from the question of whether the late 1990s productivity surge at the country level was a temporary development or the beginning of a long-term structural shift in the economy.

While average returns are high, there is a great deal of variance among firms in returns to IT investments. Complementary management practices such as decentralization of decision making, business process redesign and total quality management are found to be critical to the level of returns to IT investment achieved by firms.

Studies also show that IT capital can be substituted for other types of capital and labor, and that IT investment is associated with a shift to higher skilled workers. One explanation is that organizational computing systems have been a substitute for low- and middle-skill white collar workers while creating more demand for high-skill workers.

Firm-level studies have so far failed to show a clear link from IT investment to profitability. The failure to document these results likely stems from the inability to quantify and incorporate the various unobservable factors that determine a firm’s competitive position and outcomes.

Finally, while firm-level studies show that IT investments have a higher gross marginal product than non-IT investments, there are reasons to be skeptical of claims that firms are systematically under investing in IT. Once factors such as incomplete accounting of complementary investments, high rates of obsolescence, and risk adjustments are taken into account, the returns to IT investments are likely to look more normal. Also, the surge in IT investment since 1995 suggests that executives have recognized the value of IT capital and have adjusted their investment patterns accordingly.

IV. COUNTRY LEVEL RESEARCH

As discussed above, economists mainly use an approach called growth accounting to estimate the contribution of inputs to productivity and output. Our focus is on the contributions of IT investments to the production of goods and services. Economic growth can result from a greater level of inputs (labor and capital), improved quality of the inputs, and greater overall efficiency in the combination of inputs in production. The efficiency with which these factors of production are combined can increase as a result of improvements in production methods, such as managerial practices, organizational changes and innovative ways of producing goods and services.

The research shows that all of these factors explain some of the trends in economic growth at the level of the economy. Countries that have experienced economic growth in the last decade have had higher employment; have accumulated more physical capital, especially IT; have improved the skills of their workforce; and have improved the overall efficiency with which they employ these factors.

The key question in our analysis is the specific contribution of IT capital to this growth, both in terms of labor productivity increases via capital deepening and multifactor productivity growth.[10] In examining this question, we will distinguish between contributions from investments in IT capital by all IT-using industries and contributions from technical progress in the IT-producing industries. While there is an important conceptual distinction between the sources of productivity growth, the distinction between growth in labor productivity and MFP in empirical analyses is often a rough and ready practical one, as the researcher is limited by measurement issues, and data strengths and weaknesses. It should be pointed out that it is therefore difficult to precisely interpret the allocation of productivity improvements to capital deepening and to MFP in terms of the qualitative impacts of IT systems described in Section II.

Labor productivity growth

The first studies conducted at the country level in the late eighties and early nineties concluded that the contribution of IT to productivity and economic growth was non-existent or slight (Roach, 1987, 1989, 1991; Oliner and Sichel, 1994; Jorgenson and Stiroh, 1995). A primary explanation advanced for this conclusion was that IT investment was too small a portion of the capital stock in the economy to have substantial economic effects. For example, IT capital's share of total capital investment in nominal dollars in the U.S. was 3.5 percent in 1980 and 9 percent in 1990. During the nineties and especially in the mid-late nineties, IT capital investment increased dramatically, reaching 22% of total U.S. capital investment. As a result of this larger IT investment, new economic studies produced a more positive picture of the impacts of IT investment.

IT investments have had a major impact on labor productivity and economic growth at the country level. The U.S. economy performed extraordinarily well from 1995-2000 as

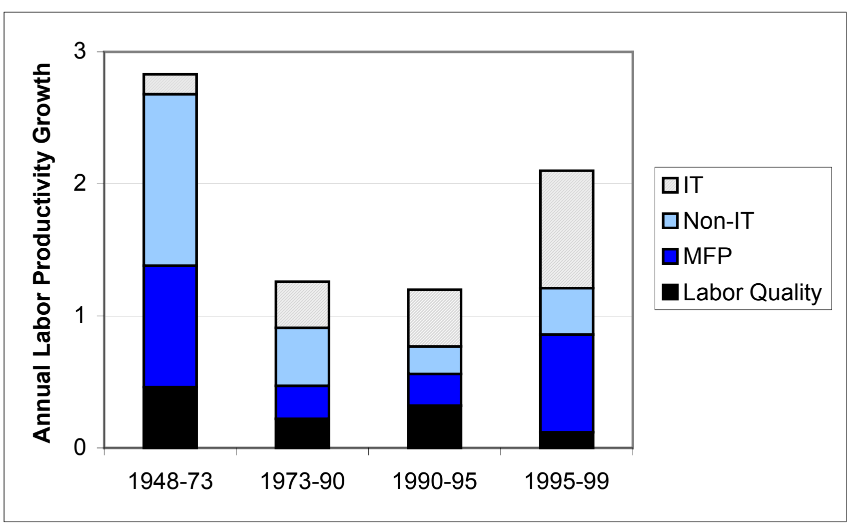
[10] We include studies derived from the National Income and Product Accounts that analyze sectoral differences in this section.

growth in labor productivity soared after a quarter century of near stagnation. Labor productivity, which grew at 1.5 percent per year in the 1973-1995 period, grew at the rate of 3.1 percent in 1995-2000. Similarly, GDP grew at 3 percent per year in the earlier period and accelerated to 4.8 percent during the later period (CEA, 2001). This acceleration in recent productivity and GDP growth has been attributed in significant part to the impact of IT investment by several macroeconomic studies (e.g., Oliner and Sichel, 2000; Jorgenson, 2000; Jorgenson and Stiroh, 2000; CEA, 2001).

There is some debate about the share of these improvements attributable to structural changes, or changes in the trend line, versus those that are due to the effects of the business cycle. In particular, short-run growth can raise both measured productivity and investment; short-run decline can reduce both. Gordon (2000) attributes a significant share of the 1995-2000 productivity growth acceleration to business cycle effects, while other studies (CEA, 2001; Stiroh, 2001) show little or no cyclical effects. These assumptions make a big difference in interpreting the magnitude of the impact of IT investment on productivity.

Although much of the current focus is on the IT-led productivity surge of the late-1990s, it is worth pointing out that these contributions are not new. While the impacts of IT capital investment were lower because of its lower share of capital stock, IT investment has contributed to U.S. economic and productivity growth for decades, even when the growth rate in labor productivity was low (Figure 1). While there continues to be a debate over the size of the IT contribution to productivity, there is convincing evidence of significant and positive long-term impacts from IT investments on national productivity.

Figure 1. Contribution of IT and non-IT capital investment to labor productivity growth



Source: Based on data from Jorgenson, 2001.

Early studies by Jorgenson and Stiroh (1995) reported a modest contribution of IT to productivity growth—about 6 percent of yearly productivity growth of 2.94 percent (Table

1) for the period 1959-1973. In subsequent periods, these researchers found the contribution of IT to be considerably greater. For example, during the period 1973-1995, Jorgenson and Stiroh (2000) found that IT contributed about 13 percent of the 3.04 percent economic growth and 27 percent of the 1.4 percent labor productivity growth in the U.S. Oliner and Sichel (2000) found slightly higher contributions (Table 1).

Table 1. Contributions of IT to GDP and productivity growth

Jorgenson & Stiroh, 2000; Jorgenson, 2001	**1959-1973**	**1973-1995**	**1995-1999**
GDP growth (annual rate)	4.32	3.04	4.08
Capital contribution (% of total)	33	50	71
IT contribution to GDP growth (% of total)	4	13	28
Productivity growth (annual rate)	2.94	1.40	2.11
IT contribution to productivity growth (%)	6	27	42
Oliner & Sichel, 2000		**1973-1995**	**1995-1999**
GDP growth (annual rate)		2.99	4.82
Capital contribution (% of total)		42	38
IT contribution to GDP growth (% of total)		17	23
Productivity growth (annual rate)		1.52	2.67
IT contribution to productivity growth (%)		31	41

Sources: Original studies, plus calculations by Bosworth and Triplett, 2000 and the authors.
These studies were selected for special focus because they are comparable in that they include similar time periods, the same methodology, and the same definition of IT to include computer hardware, software and telecommunications equipment.

The significance of these findings is that the broad and continuing use of IT has made a significant difference in long-term labor productivity growth. The Internet and electronic commerce might contribute additionally. A new study by Litan and Rivlin (2001) estimates the likely productivity impact from the Internet across eight industry sectors which account for about 70 percent of the nation's GDP. While admittedly speculative, the study estimates that the impact of the Internet over five years could translate into an annual contribution of 0.2-0.4 percent to the baseline trend of productivity growth.

The acceleration of labor productivity growth from 1995-1999 was due in part to rapid growth in IT investment. The major reason for the increased impact on productivity is simply that investment in IT has been increasing at a faster rate and the accumulated investment in IT now represents a substantially greater share of the total capital stock than in prior periods. In the period since 1995, IT capital has contributed more to the growth of the economy than it did in earlier periods. Jorgenson (2001) shows that during the period 1995-1999, IT capital contributed about twenty-eight percent of the 4.08 percent yearly economic growth and about forty-two percent of the 2.11 percent growth in labor productivity in the U.S. Oliner and Sichel (2000) estimate very similar contributions (Table 1).

The nominal share of IT investment as a percent of total business investment has grown from 2.6% in 1970 to 3.5% in 1980 to 9% in 1990 and 22% in 1999. One major factor in this increased rate of adoption of IT was an acceleration of the decline in computer prices, from an average rate of 17% annually from 1959-1995, to roughly 32% for the period 1995-1999 (Jorgenson, 2001). Clearly, the decreasing prices of IT have resulted in a significant increase in its demand, encouraging organizations to substitute IT for labor and for other forms of capital such as plant, machinery or equipment. Although IT capital is not a very large portion of total capital investment, there is no evidence that IT investment has reached a point of diminishing returns.

Labor productivity in other developed countries

While there has not been as much research comparable to that in the United States elsewhere in the world, most of the foregoing trends have also been found in other developed countries of Europe and Asia. For example, Schreyer (1999) looked at G-7 countries and found that IT made a positive contribution to productivity and economic growth in all of the countries during the period 1990-1996. Another OECD study (Daveri, 2000) updated and extended the analysis to 18 countries. While there were differences between the two studies, the story is the same—IT capital has contributed to growth, and because IT has been growing faster than labor input, it contributes to labor productivity through capital deepening.

These findings are corroborated by several larger and more robust studies done by other economists and management scientists. Two contemporary studies of 36 (plus) countries worldwide came to the interesting conclusion that wealthier, industrialized countries showed a positive and significant relationship between IT, growth and productivity, but that there was no evidence of such relationship for developing countries (Dewan and Kraemer, 1998, 2000; Pohjola, 2001). Dewan and Kraemer hypothesized that this gap was due to the low levels of IT investment relative to GDP in developing countries, and to the lack of complementary assets such as the necessary infrastructure and knowledge-base to support effective use of IT.

Labor productivity in IT-using industries

Labor productivity has increased in many industry sectors and it has increased more in industries that use IT more intensively. Nearly all of the major studies show that labor productivity growth has accelerated in many industry sectors in the 1995-1999 period over the earlier period (Jorgenson and Stiroh, 2000; CEA, 2001; Stiroh, 2001; Baily and Lawrence, 2001). One study (Gordon, 2000) found that the labor productivity gains were all concentrated in the durable goods sector, and most of that in the IT-producing industries. However, Gordon (2001) has since updated his study to include data for 2000 and now finds acceleration in labor productivity outside the durable goods sectors.

The research also shows that there is variation across industries but the overall pattern is one of positive and in some cases very substantial change (Table 2). While the overall pattern is encouraging, the results cannot be interpreted as definitive because the process of arriving at these industry estimates is inexact and productivity growth can be overestimated in one industry and underestimated in another (Stiroh, 2001; Bosworth and Triplett, 2000).

Table 2. Labor productivity growth* by industry, 1989-1999

Industry	1989-1995	1995-1999	Change
Private industries	**.88**	**2.31**	**1.43**
Agriculture, forestry, fisheries	.34	1.18	0.84
Mining	4.56	4.06	-.50
Construction	-.10	-.89	-.79
Manufacturing	3.18	4.34	1.16
Durable goods	4.34	6.84	2.51
Nondurable goods	1.65	1.07	-.59
Transportation	2.48	1.72	-.76
Trucking and warehousing	2.09	-.78	-2.82
Transportation by air	4.52	4.52	.00
Other transportation	1.51	2.14	.63
Communications	5.07	2.66	-2.41
Electric, gas and sanitary services	2.51	2.42	-.09
Wholesale trade	2.84	7.84	4.99
Retail trade	.68	4.93	4.25
Finance, insurance and real estate	1.70	2.67	.97
Finance	3.18	6.76	3.58
Insurance	-.28	.44	.72
Real estate	1.38	2.87	1.49
Services	-1.12	-.19	.93
Personal services	-1.47	1.09	2.55
Business services	-.16	1.69	1.85
Health services	-2.31	-1.06	1.26
Other services	-.72	-.71	.01
Industries by intensity of IT use			
Intense IT use	2.43	4.18	1.75
Less intense IT use	-.10	1.05	1.15

*Value added per full-time equivalent employee; average annual percent change.
Source: Council of Economic Advisors (2001).

The studies also show that this positive change in labor productivity is associated with greater IT investment. Those industries that have made greater investments in IT also experienced greater change in labor productivity. For example, as shown at the bottom of Table 2 from the CEA (2001) study, average productivity growth from 1995-1999 was four times greater (4.18% versus 1.05%) in industries with intense IT investment than in those with less intense investment. Moreover, the increase in average productivity for the industries with intense IT investment was also greater between the 1989-1995 and 1995-1999 period than it was for those with less intense investment (Table 2).

The CEA findings are reinforced by Stiroh (2001) who uses industry data to analyze the impacts of IT on labor productivity. Stiroh compares productivity gains during the nineties in 57 industry sectors and finds that IT-intensive industries (those with higher than average levels of IT capital as a share of total capital) showed a 1.3 percent higher labor productivity acceleration than other industries from the early to late 1990s, and had higher productivity growth in both periods This provides further evidence that IT use has been strongly identified with the acceleration of labor productivity in the late 1990s.

Multi-factor productivity growth in the U.S.

There has been an increase in multifactor productivity growth in the U.S. economy during the 1995-1999 period. MFP growth is the increase in aggregate output over and above that due to increases in the quantity and quality of capital and labor inputs. MFP growth may result, for example, from technical innovations in product technologies, and when a firm reengineers its supply chain, production line or distribution network in a way that increases output while utilizing the same machines, materials, and workers as before. Jorgenson (2001) estimates that annual MFP growth increased threefold from 0.24 in 1990-1994 to 0.75 in 1995-1999 for the U.S. economy.

There is considerable agreement among economists that multifactor productivity has increased in the IT producing industries (Gordon, 2000; Jorgenson and Stiroh, 2000; Oliner and Sichel, 2000; CEA, 2001). As an example, Jorgenson (2001) attributes two-thirds of the growth in MFP in the 1995-1999 period to the IT-producing sector. Specifically, he attributes the growth in MFP to continuing technical innovation (R&D) in the semiconductor and computer industries. More rapid price declines have occurred from 1994-1999 with the result that computer and telecommunications equipment prices have declined by 90 percent over the period. This increase in productivity in the IT-producing sector has naturally contributed to MFP growth in the whole economy given its increasing share of the national economy.

Multifactor productivity in the IT-using industries

On the other hand, there is some debate about whether MFP growth has also increased in the IT-using (non IT-producing) industries. Most studies attribute some multifactor productivity growth in the recent five years to the IT-using industries as well as the IT producing industries (Whelan, 2000; Jorgenson and Stiroh, 2000; Oliner and Sichel, 2000; CEA 2001; Baily and Lawrence, 2001). However, Gordon (2000) finds no evidence of MFP acceleration outside of the IT-producing and durable goods manufacturing industries.

As for the impact of IT capital on MFP, none of the studies address this issue directly. The neoclassical methodologies employed in the studies treat IT as just another form of capital whose impacts occur only through capital deepening. It is considered possible that investments in IT can have spillover effects, so that IT users capture some of the MFP gains created by the IT-producing industry. However, as Stiroh (2001) says, "Differentiating between these forces…is quite difficult and subject to potentially severe measurement problems. By focusing on labor productivity, one can gauge the impact of IT without making the difficult, and sometimes semantic, distinction between traditional capital deepening, embodied technological change and productivity spillovers."

Summary of country research

The large price/performance changes in IT equipment have stimulated increases in IT capital investment in the U.S. and other countries in the expectation of improved economic performance. The surge in IT investment during the mid- to late-nineties has led to a sharp acceleration in labor productivity growth, but it is important to recognize that IT investments have been paying off in terms of labor productivity for over thirty years. As IT has become a larger share of total capital investment by firms, so has its contribution to labor productivity and to economic growth. In recent years, growth in labor productivity and MFP in the economy has accelerated, though there is some uncertainty of the permanent improvement in trend productivity growth. Both IT-producing and IT-using industries have seen accelerations in labor productivity growth due in part to their investments in IT. Led by technological innovation, the IT-producing sector has also experienced considerable growth in MFP. There has been MFP growth in the IT-using sectors of the economy as well, but the role of IT capital investment here is unclear.

V. EVALUATION OF THE STATE OF RESEARCH

Research Methods

Production functions are mathematical representations of a production process that relate the levels of inputs in a firm, industry or economy to its output. In the studies cited in this paper, these inputs include the stock of capital inputs, both IT and non-IT capital (such as plant and equipment), and labor. Measures of output at the firm level include the revenues of a firm, and the value added by a firm, which is defined (loosely) as its revenues minus its cost of inputs. At the industry and economy level in the United States, these are aggregate quality-adjusted output measures derived by the Bureau of Economic Analysis (BEA) for use in the National Income and Product Accounts.

Growth accounting is a related application that allocates the output of an industry or economy to the inputs. In growth accounting, labor productivity growth can be attributed to changes in input quantities of IT and non-IT capital, input quality, and multifactor productivity growth. Assuming constant returns and competitive markets, output elasticities are estimated from cost shares, and MFP growth is calculated as the residual factor.

Issues with Existing Research

A careful assessment of the literature brings to the forefront a range of underlying research issues that make it difficult to precisely estimate the returns to IT investment.

Measurement and data

Accurate estimation of the returns to IT investment requires accurate measurement of the inputs and outputs in the production processes of firms and industries. As has been mentioned previously in the paper, measurement issues are quite daunting in this field. In particular, measuring outputs in the service sector, which owns the majority of IT capital, is very difficult, as is accounting for changes in the intangible attributes of products such as quality and variety in the manufacturing sector. Indeed, many have argued that returns are under-estimated due to problems in the measurement of output, and that this problem is particularly evident in service industries. At the firm level, most studies use the value added by firms (defined as revenues minus the cost of inputs) as a measure of output which may not capture the quality improvements that a firm makes in its products or services. Accurate measurement of firm outputs requires data on the outputs of firm that accounts for these improvements, as well as data on quality-adjusted prices for these outputs, which are usually unavailable. On the input side, it has been quite challenging to develop quality-adjusted price indexes for IT inputs. In the case of hardware, while measurement is complex, government agencies like the BEA, in concert with academic and computer industry economists, have made significant strides in developing quality-adjusted price indexes for computer equipment. On the other hand, it has proven to be very difficult to account for investments in software. It is not only conceptually challenging to define units of software; it is also difficult in practice to account for the large investments that firm have made in custom software. While there has been considerable progress in developing price indexes for packaged software, the same is not true for custom software. Indeed, it was only in 1999 that software was reclassified as an investment rather than an expense in the national accounts.

Data

Aggregate studies primarily rely on government statistics at the industry and economy levels. In the United States, one major source of data is the National Income and Product Accounts that track the investments and outputs of industries and the economy. Labor data are measured and published by the Bureau of Labor Statistics. While these data possess the shortcomings mentioned above, they are arguably comprehensive in that they capture virtually the entire economy and a vast majority of the measured capital investments and outputs. However, it has been exceedingly difficult for researchers to obtain accurate firm-level data. In the United States, there have been three primary sources of data on IT investments. These include the Management Productivity and Information Technology (MPIT) dataset from the Strategic Planning Institute, data from the International Data Group and from Computer Intelligence Infocorp (CII). These data have several shortcomings. For example, they include hardware categories but no software or personnel categories, and it is unknown as to what percentage of a firm's IT investment is actually reflected in this data. Firms and their holdings of IT, including categories and their definition, also change periodically making time-series analysis difficult. Moreover, these data are available only for large companies. On the output side, since there are no quality-adjusted prices for firm outputs, most studies utilize revenues or value added as measures of output. These data are available from the Compustat database, and are widely regarded as quite accurate. Finally, data on firm-specific management practices require primary data collection by the researcher.

Statistical Issues

There are estimation issues as well; a few key concerns are discussed here. In production function approaches, perhaps the most significant of these is the notion of simultaneity in investment and growth due to unobservable factors. For example, a firm with growth options may choose to invest in increasing amounts of IT to enable its growth. Statistical techniques may find evidence of a correlation between IT investment and growth, but not recognize that these are simultaneously determined by an unobservable factor – e.g., a firm's growth options – and erroneously attribute this growth to IT investment. Virtually all studies employ advanced techniques to address this concern; what is uncertain is how successful these techniques are in distinguishing these two effects.

These same problems arise with macroeconomic data: is an increase in investment a cause of an increase in GDP, or vice versa? Aggregate labor productivity tends to increase when the labor market is tight since firms try to squeeze more output from their existing workers. The very low rates of unemployment in the later 1990s would naturally lead to an increase in measured productivity. Researchers have attempted to adjust for these business cycle effects, but it is still debatable how well they have succeeded.

In spite of legitimate concerns about measurement, data, and statistical models, the evidence of positive and significant productivity gains related to IT investment is still strong. The fact that a large number of studies using different data sets and different models come to similar conclusions makes for convincing evidence. The issues raised point to difficulties in arriving at precise estimates of returns on investment, and of sorting out the relative contributions of labor productivity versus MFP. They also point to opportunities for future research.

Opportunities for Future Research

Sources of productivity growth

The research reviewed in this paper highlights a set of fundamental issues and questions that are critical to developing an understanding of the mechanisms by which IT pays off. In particular, IT can result in a productivity payoff through an impact on labor productivity via capital deepening, and in MFP growth through improvements in production methods. The first finding is consistent with a traditional neoclassical economics view which also implies that firms receive diminishing returns from continuing investment in IT as opportunities for investment decline with increasing levels of IT stock. In this view, technical progress originates exogenously in the computer industry, and ongoing investment by firms in the outputs of the IT industry drives productivity growth. On the other hand, a payoff in labor productivity via capital deepening plus MFP growth is indicative of constant or increasing returns. Such a finding requires the identification of a mechanism by which capital might not suffer from decreasing returns.[11] In particular, one explanation for this structure of returns is the possibility of spillovers in which firms benefit not just from a private investment in an asset but also from a growth in the asset stock of all firms.

[11] This notion is central to new growth theory, which focuses on endogenous growth and constant or increasing returns. c.f. Paul Romer (1986).

Spillover effects

An understanding of whether these spillovers exist and how they occur is central to developing a comprehensive framework for understanding the returns to IT investment and for developing guidelines for successful deployment of these technologies. A critical feature of this debate is whether IT is like traditional forms of capital, such as tangible assets and human capital, or whether it is more like knowledge capital, which is significantly different. In the case of traditional capital investment, returns accrue primarily to the firm making the investment and receive diminishing returns from continuing investment. On the other hand, some economists hold that knowledge capital can be owned and used by many parties simultaneously, leading to potential spillovers, and that the returns may be difficult for a single firm to capture in the presence of spillovers to other firms. These spillovers can lead to endogenous technical progress.

Clearly, IT capital has aspects of both forms of capital. As a production technology, it is similar to traditional forms of capital. In its informational and transformational roles, it is similar to knowledge capital. Best practice information regarding the management of technology, complementary organizational practices, and techniques for the application of information derived from information systems use to the management of a firm do lend themselves to use by many firms. The source of the diffusion of such knowledge is often entities such as technology user groups, academic institutions, and management consulting firms and, especially, labor mobility. It is often the case that competing firms rapidly copy IT investments by innovative firms.

Increasing returns at the firm level

At the firm level, an important question that deserves further attention is an analysis of the high returns to IT use that some firms appear to have accrued. Some evidence suggests that firms in durable goods industries have achieved substantially larger returns than firms in non-durable goods industries, while other evidence suggests that the returns to IT investment are broader and accrue to a wider range of firms if lagged payoffs are taken into account. As pointed out here, IT must have a high gross return to allow for rapid depreciation and obsolescence, and it is also the case that investments in complementary assets such as software, training and organizational transformations have been undercounted. It is critical to develop an understanding of the mechanisms by which these returns accrue to firms.

Sectoral differences

At aggregate levels, a story that is generally consistent with the traditional, neoclassical approach has been advanced. That is, in computer-using industries, the mechanism through which IT provides a payoff is increasing labor productivity via capital deepening; in the computer-producing sector, and the durable goods sector, more generally, the mechanism is primarily technical progress, measured as growth in MFP. While the evidence for this is compelling overall, there are some important unanswered questions. For one, it is unclear why some IT-intensive industries -- services and finance, insurance and real estate -- have not seen gains in labor productivity in spite of investments in IT. While the difficulty in measuring outputs in these industries is one of the likely explanations, more research is required to fully understand this result. There are remaining questions too as to the share of the gains in computer-using industries that are permanent versus those that are a result of cyclical trends. It is also somewhat unclear why durable goods industries other than the computer-producing sectors achieve MFP gains. Finally, it is not understood why technical progress has accelerated in recent years in the computer-producing sectors of the economy.

V. CONCLUSIONS

The research on payoffs from IT investments is complex, employing a number of analytical tools to study a variety of countries, industries and firms. Different studies sometimes come to conflicting conclusions, and researchers have different interpretations of what the data mean. However, beyond the complexity two fundamental implications clearly emerge.

- The productivity paradox as first formulated has definitely been put to rest. A number of studies have documented the significant impact of IT investment on the productivity of firms, industries and countries. While the so-called New Economy captured the media's attention in the late 1990s, IT investments actually have been increasing productivity for decades.

- Although returns to IT investments are positive on average, there is a wide range of performance among different companies, with some doing much better than others. There is strong evidence that investments in organizational capital through management practices such as decentralized decision making, job training and business process restructuring have a major impact on returns to IT investments. Companies need to jointly assess their investments in IT and in organizational assets, as the two are complementary.

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