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Beyond Computation: Information Technology, Organizational Transformation and Business Performance

Erik Brynjolfsson and Lorin M. Hitt

How do computers contribute to business performance and economic growth? Even today, most people who are asked to identify the strengths of computers tend to think of computational tasks like rapidly multiplying large numbers. Computers have excelled at computation since the Mark I (1939), the first modern computer, and the ENIAC (1943), the first electronic computer without moving parts. During World War II, the U.S. government generously funded research into tools for calculating the trajectories of artillery shells. The result was the development of some of the first digital computers with remarkable capabilities for calculation—the dawn of the computer age.

However, computers are not fundamentally number crunchers. They are symbol processors. The same basic technologies can be used to store, retrieve, organize, transmit, and algorithmically transform any type of information that can be digitized—numbers, text, video, music, speech, programs, and engineering drawings, to name a few. This is fortunate because most problems are not numerical problems. Ballistics, code breaking, parts of accounting, and bits and pieces of other tasks involve lots of calculation. But the everyday activities of most managers, professionals, and information workers involve other types of

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thinking. As computers become cheaper and more powerful, the business value of computers is limited less by computational capability and more by the ability of managers to invent new processes, procedures and organizational structures that leverage this capability. As complementary innovations continue to develop, the applications of computers will expand well beyond computation for the foreseeable future.

The fundamental economic role of computers becomes clearer if one thinks about organizations and markets as information processors (Galbraith, 1977; Simon, 1976; Hayek, 1945). Most of our economic institutions and intuitions emerged in an era of relatively high communications cost and limited computational capability. Information technology, defined as computers as well as related digital communication technology, has the broad power to reduce the costs of coordination, communications, and information processing. Thus, it is not surprising that the massive reduction in computing and communications costs has engendered a substantial restructuring of the economy. The majority of modern industries are being significantly affected by computerization.

As a result, information technology is best described not as a traditional capital investment, but as a "general purpose technology" (Bresnahan and Trajtenberg, 1995). In most cases, the economic contributions of general purpose technologies are substantially larger than would be predicted by simply multiplying the quantity of capital investment devoted to them by a normal rate of return. Instead, such technologies are economically beneficial mostly because they facilitate complementary innovations.

Earlier general purpose technologies, such as the telegraph, the steam engine and the electric motor, illustrate a pattern of complementary innovations that eventually lead to dramatic productivity improvements. Some of the complementary innovations were purely technological, such as Marconi's "wireless" version of telegraphy. However, some of the most interesting and productive developments were organizational innovations. For example, the telegraph facilitated the formation of geographically dispersed enterprises (Milgrom and Roberts, 1992); while the electric motor provided industrial engineers more flexibility in the placement of machinery in factories, dramatically improving manufacturing productivity by enabling workflow redesign (David, 1990). The steam engine was at the root of a broad cluster of technological and organizational changes that helped ignite the first industrial revolution.

In this paper, we review the evidence on how investments in information technology are linked to higher productivity and organizational transformation, with emphasis on studies conducted at the firm level. Our central argument is twofold: first, that a significant component of the value of information technology is its ability to enable complementary organizational investments such as business processes and work practices; second, these investments, in turn, lead to productivity increases by reducing costs and, more importantly, by enabling firms to increase output quality in the form of new products or in improvements in intangible aspects of existing products like convenience, timeliness, quality, and

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variety.[1] There is substantial evidence in both the case literature on individual firms and multi-firm econometric analyses supporting both these points, which we review and discuss in the first half of this paper. This emphasis on firm-level evidence stems in part from our own research focus but also because firm-level analysis has significant measurement advantages for examining intangible organizational investments and product and service innovation associated with computers.

Moreover, as we argue in the latter half of the paper, these factors are not well captured by traditional macroeconomic measurement approaches. As a result, the economic contributions of computers are likely to be understated in aggregate level analyses. Placing a precise number on this bias is difficult, primarily because of issues about how private, firm-level returns aggregate to the social, economy-wide benefits and assumptions required to incorporate complementary organizational factors into a growth accounting framework. However, our analysis suggests that the returns to computer investment may be substantially higher than what is assumed in traditional growth accounting exercises. Furthermore, total capital stock (including intangible assets) associated with the computerization of the economy may be understated by a factor of ten. Taken together, these considerations suggest the bias is on the same order of magnitude as the currently measured benefits of computers.

Thus, while the recent macroeconomic evidence about computer contributions is encouraging, our views are more strongly influenced by the microeconomic data. The micro data suggest that the surge in productivity that we now see in the macro statistics has its roots in over a decade of computer-enabled organizational investments. The recent productivity boom can in part be explained as a return on this large, but intangible form of capital.

Case Examples

Companies using information technology to change the way they conduct business often say that their investment in information technology complements changes in other aspects of the organization. These complementarities have a number of implications for understanding the value of computer investment. To be successful, firms typically need to adopt computers as part of a "system" or "cluster" of mutually reinforcing organizational changes (Milgrom and Roberts, 1990). Changing incrementally, either by making computer investments without organizational change, or only partially implementing some organizational changes, can create significant productivity losses as any benefits of computerization are more than outweighed by negative interactions with existing organizational practices (Brynjolfsson, Renshaw and Van Alstyne, 1997). The need for "all or nothing"

[1] For a more general treatment of the literature on information technology value, see reviews by Brynjolfsson (1993); Wilson (1995); and Brynjolfsson and Yang (1996). For a discussion of the problems in economic measurement of computers contributions at the macroeconomic level, see Baily and Gordon (1988), Siegel (1997), and Gullickson and Harper (1999).

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changes between complementary systems was part of the logic behind the organizational reengineering wave of the 1990s and the slogan "Don't Automate, Obliterate" (Hammer, 1990). It can also explain why many large scale information technology projects fail (Kemerer and Sosa, 1991), while successful information technology adopters earn significant rents.

Many of the past century's most successful and popular organizational practices reflect the historically high cost of information processing. For example, hierarchical organizational structures can reduce communications costs because they minimize the number of communications links required to connect multiple economic actors, as compared with more decentralized structures (Malone, 1987; Radner, 1993). Similarly, producing simple, standardized products is an efficient way to utilize inflexible, scale-intensive manufacturing technology. However, as the cost of automated information processing has fallen by over 99.9 percent since the 1960s, it is unlikely that the work practices of the previous era will also be the same ones that best leverage the value of cheap information and flexible production. In this spirit, Milgrom and Roberts (1990) construct a model in which firms' transition from "mass production" to flexible, computer-enabled, "modern manufacturing" is driven by exogenous changes in the price of information technology. Similarly, Bresnahan (1999) and Bresnahan, Brynjolfsson and Hitt (2000) show how changes in information technology costs and capabilities lead to a cluster of changes in work organization and firm strategy that increase the demand for skilled labor.

In this section we will discuss case evidence on three aspects of how firms have transformed themselves by combining information technology with changes in work practices, strategy, and products and services; they have transformed the firm, supplier relations, and the customer relationship. These examples provide qualitative insights into the nature of the changes, making it easier to interpret the more quantitative econometric evidence that follows.

Transforming the Firm

The need to match organizational structure to technology capabilities and the challenges of making the transition to an information technology-intensive production process is concisely illustrated by a case study of "MacroMed" (a pseudonym), a large medical products manufacturer (Brynjolfsson, Renshaw and Van Alstyne, 1997). In a desire to provide greater product customization and variety, MacroMed made a large investment in computer integrated manufacturing. This investment also coincided with an enumerated list of other major changes including: the elimination of piece rates, giving workers authority for scheduling machines, changes in decision rights, process and workflow innovation, more frequent and richer interactions with customers and suppliers, increased lateral communication and teamwork, and other changes in skills, processes, culture, and structure (see Table 1).

However, the new system initially fell well short of management expectations for greater flexibility and responsiveness. Investigation revealed that line workers still retained many elements of the now-obsolete old work practices, not necessarily from any conscious effort to undermine the change effort, but simply as an

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Table 1
Work Practices at MacroMed as Described in the Corporate Vision Statement
(introduction of computer-based equipment was accompanied by a large set of complementary changes)

Principles of the "old" factory	*Principles of the "new" factory*
• Designated equipment	• Flexible computer-based equipment
• Large inventories	• Low inventories
• Pay tied to amount produced	• All operators paid same flat rate
• Keep line running no matter what	• Stop line if not running at speed
• Thorough final inspection by quality assurance	• Operators responsible for quality
• Raw materials made in-house	• All materials outsourced
• Narrow job functions	• Flexible job responsibilities
• Areas separated by machine type	• Areas organized in work cells
• Salaried employees make decisions	• All employees contribute ideas
• Hourly workers carry them out	• Supervisors can fill in on line
• Functional groups work independently	• Concurrent engineering
• Vertical communication flow	• Line rationalization
• Several management layers (6)	• Few management layers (3–4)

inherited pattern. For example, one earnest and well-intentioned worker explained that "the key to productivity is to avoid stopping the machine for product changeovers." While this heuristic was valuable with the old equipment, it negated the flexibility of the new machines and created large work-in-process inventories. Ironically, the new equipment was sufficiently flexible that the workers were able to get it to work much like the old machines! The strong complementarities within the old cluster of work practices and within the new cluster greatly hindered the transition from one to the other.

Eventually, management concluded that the best approach was to introduce the new equipment in a "greenfield" site with a handpicked set of young employees who were relatively unencumbered by knowledge of the old practices. The resulting productivity improvements were significant enough that management ordered all the factory windows painted black to prevent potential competitors from seeing the new system in action. While other firms could readily buy similar computer-controlled equipment, they would still have to make the much larger investments in organizational learning before fully benefiting from them and the exact recipe for achieving these benefits was not trivial to invent (see Brynjolfsson, Renshaw, and Van Alstyne, 1997 for details). Similarly, large changes in work practices have been documented in case studies of information technology adoption in a variety of settings (Hunter, Bernhardt, Hughes and Skuratowicz, 2000; Levy, Beamish, Murnane and Autor, 2000; Malone and Rockart, 1991; Murnane, Levy and Autor, 1999; Orlikowski, 1992).

Changing Interactions with Suppliers

Due to problems coordinating with external suppliers, large firms often produce many of their required inputs in-house. General Motors is the classic example

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of a company whose success was facilitated by high levels of vertical integration. However, technologies such as electronic data interchange, Internet-based procurement systems, and other interorganizational information systems have significantly reduced the cost, time and other difficulties of interacting with suppliers. For example, firms can place orders with suppliers and receive confirmations electronically, eliminating paperwork and the delays and errors associated with manual processing of purchase orders (Johnston and Vitale, 1988). However, even greater benefits can be realized when interorganizational systems are combined with new methods of working with suppliers.

An early successful interorganizational system is the Baxter ASAP system, which lets hospitals electronically order supplies directly from wholesalers (Vitale and Konsynski, 1988; Short and Venkatraman, 1992). The system was originally designed to reduce the costs of data entry—a large hospital could generate 50,000 purchase orders annually which had to be written out by hand by Baxter's field sales representatives at an estimated cost of $25-35 each. However, once Baxter computerized its ordering and had data available on levels of hospital stock, it took increasing responsibility for the entire supply operation: designing stockroom space, setting up computer-based inventory systems, and providing automated inventory replenishment. The combination of the technology and the new supply chain organization substantially improved efficiency for both Baxter (no paper invoices, predictable order flow) and the hospitals (elimination of stockroom management tasks, lower inventories, and less chance of running out of items). Later versions of the ASAP system let users order from other suppliers, creating an electronic marketplace in hospital supplies.

ASAP was directly associated with costs savings on the order of $10 to $15 million per year, which allowed them to recover rapidly the $30 million up front investment and approximately $3 million annual operating costs. However, management at Baxter believed that even greater benefits were being realized through incremental product sales at the 5500 hospitals that had installed the ASAP system, not to mention the possibility of a reduction of logistics costs borne by the hospitals themselves, an expense which consumes as much as 30 percent of a hospital's budget.

Computer-based supply chain integration has been especially sophisticated in the consumer packaged goods industries. Traditionally, manufacturers promoted products such as soap and laundry detergent by offering discounts, rebates, or even cash payments to retailers to stock and sell their products. Because many consumer products have long shelf lives, retailers tended to buy massive amounts during promotional periods, which increased volatility in manufacturing schedules and distorted manufacturers' view of their market. In response, manufacturers sped up their packaging changes to discourage stockpiling of products and developed internal audit departments to monitor retailers' purchasing behavior for contractual violations (Clemons, 1993).

To eliminate these inefficiencies, Procter and Gamble pioneered a program called "efficient consumer response" (McKenney and Clark, 1995). In this approach, each retailer's checkout scanner data goes directly to the manufacturer;

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ordering, payments, and invoicing are fully automated through electronic data interchange; products are continuously replenished on a daily basis; and promotional efforts are replaced by an emphasis on "everyday low pricing." Manufacturers also involved themselves more in inventory decisions and moved toward "category management," where a lead manufacturer would take responsibility for an entire retail category (say, laundry products), determining stocking levels for their own and other manufacturers' products, as well as complementary items.

These changes, in combination, greatly improved efficiency. Consumers benefited from lower prices and increased product variety, convenience, and innovation. Without the direct computer-computer links to scanner data and the electronic transfer of payments and invoices, they could not have attained the levels of speed and accuracy needed to implement such a system.

Technological innovations related to the commercialization of the Internet have dramatically decreased the cost of building electronic supply chain links. Computer-enabled procurement and on-line markets enable a reduction in input costs through a combination of reduced procurement time and more predictable deliveries, which reduces the need for buffer inventories and reduces spoilage for perishable products, reduced price due to increasing price transparency and the ease of price shopping, and reduced direct costs of purchase order and invoice processing. Where they can be implemented, these innovations are estimated to lower the costs of purchased inputs by 10 to 40 percent, depending on the industry (Goldman Sachs, 1999).

Some of these savings clearly represent a redistribution of rents from suppliers to buyers, with little effect on overall economic output. However, many of the other changes represent direct improvements in productivity through greater production efficiency and indirectly by enabling an increase in output quality or variety without excessive cost. To respond to these opportunities, firms are restructuring their supply arrangements and placing greater reliance on outside contractors. Even General Motors, once the exemplar of vertical integration, has reversed course and divested its large internal suppliers. As one industry analyst recently stated, "What was once the greatest source of strength at General Motors—its strategy of making parts in-house—has become its greatest weakness" (Schnapp, 1998). To get some sense of the magnitude of this change, the spinoff in 1999 of Delphi Automotive Systems, only one of GM's many internal supply divisions, created a separate company that by itself has $28 billion in sales.

Changing Customer Relationships

The Internet has opened up a new range of possibilities for enriching interactions with customers. Dell Computer has succeeded in attracting customer orders and improving service by placing configuration, ordering, and technical support capabilities on the web (Rangan and Bell, 1999). It coupled this change with systems and work practice changes that emphasize just-in-time inventory management, build-to-order production systems, and tight integration between sales and production planning. Dell has implemented a consumer-driven build-to-order business model, rather than using the traditional build-to-stock model of selling

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computers through retail stores, which gives Dell as much as a 10 percent advantage over its rivals in production cost. Some of these savings represent the elimination of wholesale distribution and retailing costs. Others reflect substantially lower levels of inventory throughout the distribution channel. However, a subtle but important by-product of these changes in production and distribution is that Dell can be more responsive to customers. When Intel releases a new microprocessor, as it does several times each year, Dell can sell it to customers within seven days compared to eight weeks or more for some less Internet-enabled competitors. This is a nontrivial difference in an industry where adoption of new technology and obsolescence of old technology is rapid, margins are thin, and many component prices drop by 3 to 4 percent each month.

Other firms have also built closer relations with their customer via the web and related technologies. For instance, web retailers like Amazon.com provide personalized recommendations to visitors and allow them to customize numerous aspects of their shopping experience. As described by Denise Caruso (1998), "Amazon's on-line account maintenance system provides its customers with secure access to everything about their account at any time. [S]uch information flow to and from customers would paralyze most old-line companies." Merely providing Internet access to a traditional bookstore would have had a relatively minimal impact without the cluster of other changes implemented by firms like Amazon.

An increasingly ubiquitous example is using the web for handling basic customer inquiries. For instance, UPS now handles a total of 700,000 package tracking requests via the Internet every day. It costs UPS 10¢ per piece to serve that information via the Web vs. $2 to provide it over the phone (Seybold and Marshak, 1998). Consumers benefit, too. Because customers find it easier to track packages over the web than via the phone, UPS estimates that two-thirds of the web users would not have bothered to check on their packages if they did not have web access.

Large-Sample Empirical Evidence on Information Technology, Organization and Productivity

The case study literature offers many examples of strong links between information technology and investments in complementary organizational practices. However, to reveal general trends and to quantify the overall impact, we must examine these effects across a wide range of firms and industries. In this section we explore the results from large-sample statistical analyses. First, we examine studies on the direct relationship between information technology investment and business value. We then consider studies that measured organizational factors and their correlation with information technology use, as well as the few initial studies that have linked this relationship to productivity increases.

Information Technology and Productivity

Much of the early research on the relationship between technology and productivity used economy-level or sector-level data and found little evidence of a

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relationship. For example, Roach (1987) found that while computer investment per white-collar worker in the service sector rose several hundred percent from 1977 to 1989, output per worker, as conventionally measured, did not increase discernibly. In several papers, Morrison and Berndt examined Bureau of Economic Analysis data for manufacturing industries at the two-digit SIC level and found that the gross marginal product of "high-tech capital" (including computers) was less than its cost and that in many industries these supposedly labor-saving investments were associated with an increase in labor demand (Berndt and Morrison, 1995; Morrison, 1996). Robert Solow (1987) summarized this kind of pattern in his well-known remark: "[Y]ou can see the computer age everywhere except in the productivity statistics."

However, by the early 1990s, analyses at the firm-level were beginning to find evidence that computers had a substantial effect on firms' productivity levels. Using data from over 300 large firms over the period 1988-92, Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995) estimated production functions that use the firm's output (or value-added) as the dependent variable and include ordinary capital, information technology capital, ordinary labor, information technology labor, and a variety of dummy variables for time, industry, and firm.[2] The pattern of these relationships is summarized in Figure 1, which compares firm-level information technology investment with multifactor productivity (excluding computers) for the firms in the Brynjolfsson and Hitt (1995) dataset. There is a clear positive relationship, but also a great deal of individual variation in firms' success with information technology.

Estimates of the average annual contribution of computer capital to total output generally exceed $.60 per dollar of capital stock often by a substantial margin, depending on the analysis and specification (Brynjolfsson and Hitt, 1995, 1996; Lichtenberg, 1995; Dewan and Min, 1997). These estimates are statistically different from zero, and in most cases significantly exceed the expected rate of return of about $.42 (the Jorgensonian rental price of computers—see Brynjolfsson and Hitt, 2000). This suggests either abnormally high returns to investors or the existence of unmeasured costs or barriers to investment. Similarly, most estimates of the contribution of information systems labor to output exceed $1 for every $1 of labor costs.

Several researchers have also examined the returns to information technology using data on the use of various technologies rather than the size of the investment. Greenan and Mairesse (1996) matched data on French firms and workers to measure the relationship between a firm's productivity and the fraction of its employees who report using a personal computer at work. Their estimates of computers' contribution to output are consistent with earlier estimates of the computer's output elasticity.

Other micro-level studies have focused on the use of computerized manufac-

[2] These studies assumed a standard form (Cobb-Douglas) for the production function, and measured the variables in logarithms. Later work using different functional forms, such as the transcendental logarithmic (translog) production function, has little effect on the measurement of output elasticities.

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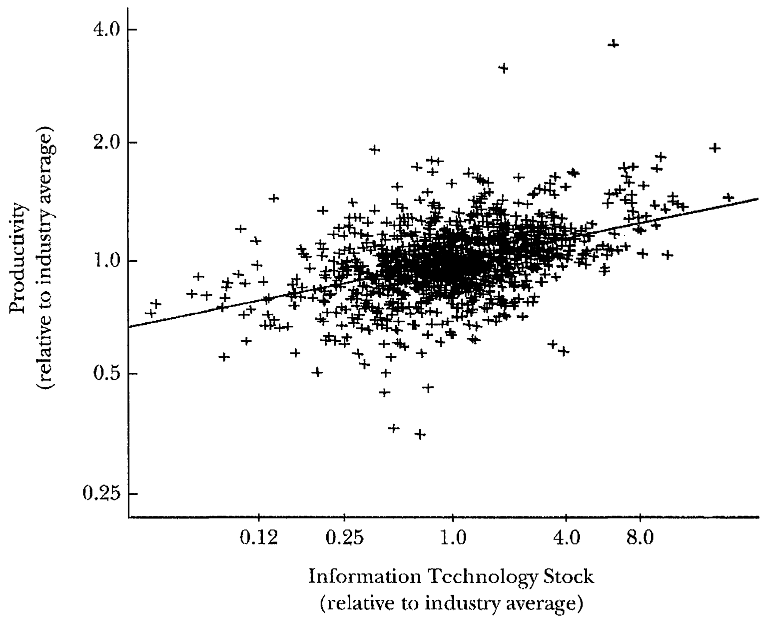
Figure 1
Productivity Versus Information Technology Stock (Capital plus Capitalized Labor) for Large Firms (1988–1992), Adjusted for Industry



turing technologies. Kelley (1994) found that the most productive metal-working plants use computer-controlled machinery. Black and Lynch (1996) found that plants where a larger percentage of employees use computers are more productive in a sample containing multiple industries. Computerization has also been found to increase productivity in government activities both at the process level, such as package sorting at the post office or toll collection (Muhkopadhyay, Rajiv and Srinivasan, 1997) and at higher levels of aggregation (Lehr and Lichtenberg, 1998).

Taken collectively, these studies suggest that information technology is associated with substantial increases in output and productivity. Questions remain about the mechanisms and direction of causality in these studies. Perhaps instead of information technology causing greater output, "good firms" or average firms with unexpectedly high sales disproportionately spend their windfall on computers. For example, while Doms, Dunne and Troske (1997) found that plants using more advanced manufacturing technologies had higher productivity and wages, they also found that this was commonly the case even before the technologies were introduced.

Efforts to disentangle causality have been limited by the lack of good instrumental variables for factor investment at the firm-level. However, attempts to correct for this bias using available instrumental variables typically increase the estimated coefficients on information technology even further (for example, Brynjolfsson and Hitt, 1996; 2000). Thus, it appears that reverse causality is not driving the results: firms with an unexpected increase in free cash flow invest in other factors, such as labor, before they change their spending on information technol-

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ogy. Nonetheless, as the case studies underscore, there appears to be a fair amount of causality in both directions—certain organizational characteristics make information technology adoption more likely and vice versa.

The firm-level productivity studies can shed some light on the relationship between information technology and organizational restructuring. For example, productivity studies consistently find that the output elasticities of computers exceed their (measured) input shares. One explanation for this finding is that the output elasticities for information technology are about right, but the productivity studies are underestimating the input quantities because they neglect the role of unmeasured complementary investments. Dividing the output of the whole set of complements by only the factor share of information technology will imply disproportionately high rates of return for information technology.[3]

A variety of other evidence suggests that hidden assets play an important role in the relationship between information technology and productivity. Brynjolfsson and Hitt (1995) estimated a firm fixed effects productivity model. This method can be interpreted as dividing firm-level information technology benefits into two parts; one part is due to variation in firms' information technology investments over time, the other to fixed firm characteristics. Brynjolfsson and Hitt found that in the firm effects model, the coefficient on information technology was about 50 percent lower, compared to the results of an ordinary least squares regression, while the coefficients on the other factors, capital and labor, changed only slightly. This change suggests that unmeasured and slowly changing organizational practices (the "fixed effect") significantly affect the returns to information technology investment.

Another indirect implication from the productivity studies comes from evidence that effects of information technology are substantially larger when measured over longer time periods. Brynjolfsson and Hitt (2000) examined the effects of information technology on productivity *growth* rather than productivity *levels*, which had been the emphasis in most previous work, using data that included more than 600 firms over the period 1987 to 1994. When one-year differences in information technology are compared to one-year differences in firm productivity, the measured benefits of computers are approximately equal to their measured costs. However, the measured benefits rise by a factor of two to eight as longer time periods are considered, depending on the econometric specification used. One interpretation of these results is that short-term returns represent the direct effects of information technology investment, while the longer-term returns represent the effects of information technology when combined with related investments in organizational change. Further analysis, based on earlier results by Schankerman (1981) in the R&D context, suggested that these omitted factors were not simply information technology investments and complements that were erroneously misclassified as capital or labor. Instead, to be consistent with the econometric results, the omitted factors had to have been accumulated in ways that would not appear on

[3] Hitt (1996) and Brynjolfsson and Hitt (2000) present a formal analysis of this issue.

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the current balance sheet. Firm-specific human capital and "organizational capital" are two examples of omitted inputs that would fit this description.[4]

A final perspective on the value of these organizational complements to information technology can be found using financial market data, drawing on the literature on Tobin's *q*. This approach measures the rate of return of an asset indirectly, based on comparing the stock market value of the firm to the replacement value of the various capital assets it owns. Typically, Tobin's *q* has been employed to measure the relative value of observable assets such as R&D or physical plant. However, as suggested by Hall (1999a, b), Tobin's *q* can also be viewed as providing a measure of the total quantity of capital, including the value of "technology, organization, business practices, and other produced elements of successful modern corporation." Using an approach along these lines, Brynjolfsson and Yang (1997) found that while one dollar of ordinary capital is valued at approximately one dollar by the financial markets, one dollar of information technology capital appears to be correlated with on the order of $10 of additional stock market value for Fortune 1000 firms using data spanning 1987 to 1994. Since these results, for the most part, apply to large, established firms rather than new high-tech start-ups, and since they predate most of the massive increase in market valuations for technology stocks in the late 1990s, these results are not likely to be sensitive to the possibility of a recent "high-tech stock bubble."

A more likely explanation for these results is that information technology capital is disproportionately associated with intangible assets like the costs of developing new software, populating a database, implementing a new business process, acquiring a more highly skilled staff, or undergoing a major organizational transformation, all of which go uncounted on a firm's balance sheet. In this interpretation, for every dollar of information technology capital, the typical firm has also accumulated about $9 in additional intangible assets. A related explanation is that firms must occur substantial "adjustment costs" before information technology is effective. These adjustment costs drive a wedge between the value of a computer resting on the loading dock and one that is fully integrated into the organization.

The evidence from both the productivity and Tobin's *q* analyses provides some insights into the properties of information technology-related intangible assets, even if we cannot measure these assets directly. Such assets are large, potentially several multiples of the measured information technology investment. They are unmeasured in the sense that they do not appear as a capital asset or as other components of firm input, although they do appear to be unique characteristics of particular firms as opposed to industry effects. Finally, they have more effect in the long term than the short term, suggesting that multiple years of adaptation and investment is required before their influence is maximized.

[4] Part of the difference in coefficients between short and long difference specifications could also be explained by measurement error (which tends to average out over longer time periods). Such errors-in-variables can bias down coefficients based on short differences, but the size of the change is too large to be attributed solely to this effect (Brynjolfsson and Hitt, 2000).

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Direct Measurement of the Interrelationship between Information Technology and Organization

Some studies have attempted to measure organizational complements directly, and to determine whether they are correlated with information technology investment, or whether firms that combine complementary factors have better economic performance. Finding correlations between information technology and organizational change, or between these factors and measures of economic performance, is not sufficient to prove that these practices are complements, unless a full structural model specifies the production relationships and demand drivers for each factor. Athey and Stern (1997) discuss issues in the empirical assessment of complementarity relationships. However, after empirically evaluating possible alternative explanations and combining correlations with performance analyses, complementarities are often the most plausible explanation for observed relationships between information technology, organizational factors, and economic performance.

The first set of studies in this area focuses on correlations between use of information technology and extent of organizational change. An important finding is that information technology investment is greater in organizations that are decentralized and have a greater investment in human capital. For example, Bresnahan, Brynjolfsson and Hitt (2000) surveyed approximately 400 large firms to obtain information on aspects of organizational structure like allocation of decision rights, workforce composition, and investments in human capital. They found that greater levels of information technology are associated with increased delegation of authority to individuals and teams, greater levels of skill and education in the workforce, and greater emphasis on pre-employment screening for education and training. In addition, they find that these work practices are correlated with each other, suggesting that they are part of a complementary work system. Kelley (1994) found that the use of programmable manufacturing equipment is correlated with several aspects of human resource practices.

Research on jobs within specific industries has begun to explore the mechanisms within organizations that create these complementarities. Drawing on a case study on the automobile repair industry, Levy, Beamish, Murnane and Autor (2000) argue that computers are most likely to substitute for jobs that rely on rule-based decision-making while complementing nonprocedural cognitive tasks. In banking, researchers have found that many of the skill, wage and other organizational effects of computers depend on the extent to which firms couple computer investment with organizational redesign and other managerial decisions (Hunter, Bernhardt, Hughes and Skuratowicz, 2000; Murnane, Levy and Autor, 1999). Researchers focusing at the establishment level have also found complementarities between existing technology infrastructure and firm work practices to be a key determinant of the firm's ability to incorporate new technologies (Bresnahan and Greenstein, 1997); this also suggests a pattern of mutual causation between computer investment and organization.

A variety of industry-level studies also show a strong connection between investment in high technology equipment and the demand for skilled, educated workers (Berndt, Morrison and Rosenblum, 1992; Berman, Bound and Griliches,

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1994; Autor, Katz and Krueger, 1998). Again, these findings are consistent with the idea that increasing use of computers is associated with a greater demand for human capital.

Several researchers have also considered the effect of information technology on macro-organizational structures. They have typically found that greater levels of investment in information technology are associated with smaller firms and less vertical integration. Brynjolfsson, Malone, Gurbaxani and Kambil (1994) found that increases in the level of information technology capital in an economic sector were associated with a decline in average firm size in that sector, consistent with information technology leading to a reduction in vertical integration. Hitt (1999), examining the relationship between a firm's information technology capital stock and direct measures of its vertical integration, arrived at similar conclusions. These results corroborate earlier case analyses and theoretical arguments that suggested that information technology would be associated with a decrease in vertical integration because it lowers the costs of coordinating externally with suppliers (Malone, Yates and Benjamin, 1987; Gurbaxani and Whang, 1991; Clemons and Row, 1992).

One difficulty in interpreting the literature on correlations between information technology and organizational change is that some managers may be predisposed to try every new idea and some managers may be averse to trying anything new at all. In such a world, information technology and a "modern" work organization might be correlated in firms because of the temperament of management, not because they are economic complements. To rule out this sort of spurious correlation, it is useful to bring measures of productivity and economic performance into the analysis. If combining information technology and organizational restructuring is economically justified, then firms that adopt these practices as a system should outperform those that fail to combine information technology investment with appropriate organizational structures.

In fact, firms that adopt decentralized organizational structures and work structures do appear to have a higher contribution of information technology to productivity (Bresnahan, Brynjolfsson and Hitt, 2000). For example, firms that are more decentralized than the median firm (as measured by individual organizational practices and by an index of such practices), have, on average, a 13 percent greater information technology elasticity and a 10 percent greater investment in information technology than the median firm. Firms that are in the top half of *both* information technology investment and decentralization are on average 5 percent more productive than firms that are above average only in information technology investment or only in decentralization.

Similar results also appear when economic performance is measured as stock market valuation. Firms in the top third of decentralization have a 6 percent higher market value after controlling for all other measured assets; this is consistent with the theory that organizational decentralization behaves like an intangible asset. Moreover, the stock market value of a dollar of information technology capital is between $2 and $5 greater in decentralized firms than in centralized firms (per standard deviation of the decentralization measure), and as shown in Figure 2 this

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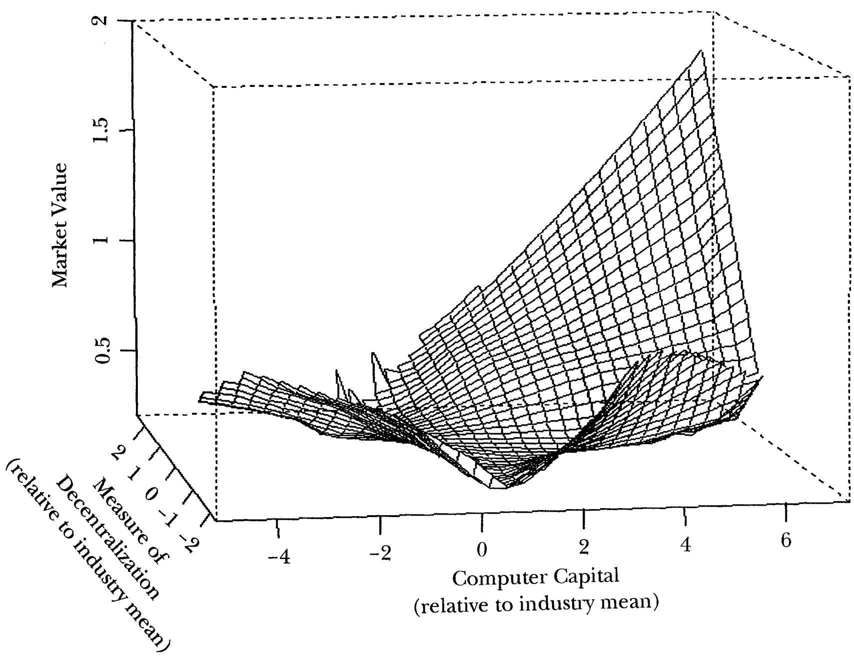
Figure 2
Market Value as a Function of Information Technology and Work Organization



Source: This graph was produced by nonparametric local regression models using data from Brynjolfsson, Hitt and Yang (2000).

relationship is particularly striking for firms that are simultaneously extensive users of information technology and highly decentralized (Brynjolfsson, Hitt and Yang, 2000).

The weight of the firm-level evidence shows that a combination of investment in technology and changes in organizations and work practices facilitated by these technologies contributes to firms' productivity growth and market value. However, much work remains to be done in categorizing and measuring the relevant changes in organizations and work practices, and relating them to information technology and productivity.

The Divergence of Firm-level and Aggregate Studies on Information Technology and Productivity

While the evidence indicates that information technology has created substantial value for firms that have invested in it, it has sometimes been a challenge to link these benefits to macroeconomic performance. A major reason for the gap in interpretation is that traditional growth accounting techniques focus on the (relatively) observable aspects of output, like price and quantity, while neglecting the

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intangible benefits of improved quality, new products, customer service and speed. Similarly, traditional techniques focus on the relatively observable aspects of investment, such as the price and quantity of computer hardware in the economy, and neglect the much larger intangible investments in developing complementary new products, services, markets, business processes, and worker skills. Paradoxically, while computers have vastly improved the ability to collect and analyze data on almost any aspect of the economy, the current computer-enabled economy has become increasingly difficult to measure using conventional methods. Nonetheless, standard growth accounting techniques provide a useful starting point for any assessment or for the contribution of information technology to economic growth.

Several studies of the contribution of information technology concluded that technical progress in computers contributed roughly 0.3 percentage points per year to real output growth when data from the 1970s and 1980s were used (Jorgenson and Stiroh, 1995; Oliner and Sichel, 1994; Brynjolfsson, 1996).

Much of the estimated growth contribution comes directly from the large quality-adjusted price declines in the computer producing industries. The nominal value of purchases of information technology hardware in the United States in 1997 was about 1.4 percent of GDP. Since the quality-adjusted prices of computers decline by about 25 percent per year, simply spending the same nominal share of GDP as in previous years represents an annual productivity increase for the real GDP of 0.3 percentage points (that is, $1.4 \times .25 = .35$). A related approach is to look at the effect of information technology on the GDP deflator. Reductions in inflation, for a given amount of growth in output, imply proportionately higher real growth and, when divided by a measure of inputs, higher productivity growth as well. Gordon (1998, p. 4) calculates that "computer hardware is currently contributing to a reduction of U.S. inflation at an annual rate of almost 0.5 percent per year, and this number would climb toward one percent per year if a broader definition of information technology, including telecommunications equipment, were used."

More recent growth accounting analyses by the same authors have linked the recent surge in measured productivity in the U.S. to increased investments in information technology. Using similar methods as in their earlier studies, Oliner and Sichel (this issue) and Jorgenson and Stiroh (1999) find that the annual contribution of computers to output growth in the second half of the 1990s is closer to 1.0 or 1.1 percentage points per year. Gordon (this issue) makes a similar estimate. This is a large contribution for any single technology, although researchers have raised concerns that computers are primarily an intermediate input and that the productivity gains are disproportionately visible in computer-producing industries as opposed to computer-using industries. For instance, Gordon notes that after he makes adjustments for the business cycle, capital deepening and other effects, there has been virtually no change in the rate of productivity growth outside of the durable goods sector. Jorgenson and Stiroh ascribe a larger contribution to computer-using industries, but still not as great as in the computer-producing industries.

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Should we be disappointed by the productivity performance of the downstream firms?

Not necessarily. Two points are worth bearing in mind when comparing upstream and downstream sectors. First, the allocation of productivity depends on the quality-adjusted transfer prices used. If a high deflator is applied, the upstream sectors get credited with more output and productivity in the national accounts, but the downstream firms get charged with using more inputs and thus have less productivity. Conversely, a low deflator allocates more of the gains to the downstream sector. In both cases, the increases in the total productivity of the economy are, by definition, identical. Since it is difficult to compute accurate deflators for complex, rapidly changing intermediate goods like computers, one must be careful in interpreting the allocation of productivity across producers and users.[5]

The second point is more semantic. Arguably, downstream sectors are delivering on the information technology revolution by simply maintaining levels of measured total factor productivity growth in the presence of dramatic changes in the costs, nature and mix of intermediate computer goods. This reflects a success in costlessly converting technological innovations into real output that benefits end consumers. If a firm maintains a constant nominal information technology budget in the face of 50 percent information technology price declines over two years, it is treated in the national accounts as using 100 percent more real information technology input for production. A commensurate increase in real output is required merely to maintain the same measured productivity level as before. Such an output increase is not necessarily automatic since it requires a significant change in the input mix and organization of production. In the presence of adjustment costs and imperfect output measures, one might reasonably have expected measured productivity to *decline* initially in downstream sectors as they absorb a rapidly changing set of inputs and introduce new products and services.

Regardless of how the productivity benefits are allocated, these studies show that a substantial part of the upturn in measured productivity of the economy as a whole can be linked to increased real investments in computer hardware and declines in their quality-adjusted prices. However, there are several key assumptions implicit in economy- or industry-wide growth accounting approaches which can have a substantial influence on their results, especially if one seeks to know whether investment in computers are increasing productivity as much as alternate possible investments. The standard growth accounting approach begins by assuming that all inputs earn "normal" rates of return. Unexpected windfalls, whether the discovery of a single new oil field, or the invention of a new process which makes oil fields obsolete, show up not in the growth contribution of inputs but as changes in the

[5] It is worth noting that if the exact quality change of an intermediate good is mismeasured, then the total productivity of the economy is not affected, only the allocation between sectors. However, if computer-using industries take advantage of the radical change in input in their quality to introduce new quality levels output (or entirely new goods) and these changes are not fully reflected in final output deflators, then total productivity will be underestimated. In periods of rapid technological change, both phenomena can be expected.

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multifactor productivity residual. By construction, an input can contribute more to output in these analyses only by growing rapidly, not by having an unusually high net rate of return.

Changes in multifactor productivity growth, in turn, depend on accurate measures of final output. However, nominal output is affected by whether firm expenditures are expensed, and therefore deducted from value-added, or capitalized and treated as investment. As emphasized throughout this paper, information technology is only a small fraction of a much larger complementary system of tangible and intangible assets. However, current statistics typically treat the accumulation of intangible capital assets, such as new business processes, new production systems and new skills, as expenses rather than as investments. This leads to a lower level of measured output in periods of net capital accumulation. Second, current output statistics disproportionately miss many of the gains that information technology has brought to consumers such as variety, speed, and convenience. We will consider these issues in turn.

The magnitude of investment in intangible assets associated with computerization may be large. Analyses of 800 large firms by Brynjolfsson and Yang (1997) suggest that the ratio of intangible assets to information technology assets may be 10 to 1. Thus, the $167 billion in computer capital recorded in the U.S. national accounts in 1996 may have actually been only the tip of an iceberg of $1.67 trillion of information technology-related complementary assets in the United States.

Examination of individual information technology projects indicates that the 10:1 ratio may even be an underestimate in many cases. For example, a survey of a common category of software projects—namely, "enterprise resource planning"—found that the average spending on computer hardware accounted for less than 4 percent of the typical start-up cost of $20.5 million, while software licenses and development were another 16 percent of total costs (Gormely et al., 1998). The remaining costs included hiring outside and internal consultants to help design new business processes and to train workers in the use of the system. The time of existing employees, including top managers, that went into the overall implementation were not included, although it too is typically quite substantial.

The up-front costs were almost all treated as current expenses by the companies undertaking the implementation projects. However, insofar as the managers who made these expenditures expected them to pay for themselves only over several years, the nonrecurring costs are properly thought of as investments, not expenses, when considering the impact on economic growth. In essence, the managers were adding to the nation's capital stock not only of easily visible computers, but also of less visible business processes and worker skills.

How might these measurement problems affect economic growth and productivity calculations? In a steady state, it makes little difference, because the amount of new organizational investment in any given year is offset by the "depreciation" of organizational investments in previous years. The net change in capital stock is zero. Thus, in a steady state, classifying organizational investments as expenses does not bias overall output growth as long as it is done consistently from year to year. However, the economy has hardly been in a steady state with respect to comput-

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ers and their complements. Instead, the U.S. economy has been rapidly adding to its stock of both types of capital. To the extent that this net capital accumulation has not been counted as part of output, output and output growth have been underestimated.

The software industry offers a useful example of the impact of classifying a category of spending as expense or investment. Historically, efforts on software development have been treated as expenses, but recently the government has begun recognizing that software is an intangible capital asset. Software investment by U.S. businesses and governments grew from $10 billion in 1979 to $159 billion in 1998 (Parker and Grimm, 2000). Properly accounting for this investment has added 0.15 to 0.20 percentage points to the average annual growth rate of real GDP in the 1990s. While capitalizing software is an important improvement in our national accounts, software is far from the only, or even most important, complement to computers.

If the wide array of intangible capital costs associated with computers were treated as investments rather than expenses, the results would be striking. According to some preliminary estimates from Yang (2000), building on estimates of the intangible asset stock derived from stock market valuations of computers, the true growth rate of U.S. GDP, after accounting for the intangible complements to information technology hardware, has been increasingly underestimated by an average of over 1 percent per year since the early 1980s, with the underestimate getting worse over time as net information technology investment has grown. Productivity growth has been underestimated by a similar amount. This reflects the large net increase in intangible assets of the U.S. economy associated with the computerization that was discussed earlier. Over time, the economy earns returns on past investment, converting it back into consumption. This has the effect of raising GDP growth as conventionally measured by a commensurate amount even if the "true" GDP growth remains unchanged.

While the quantity of intangible assets associated with information technology is difficult to estimate precisely, the central lesson is that these complementary changes are very large and cannot be ignored in any realistic attempt to estimate the overall economic contributions of information technology.

The productivity gains from investments in new information technology are underestimated in a second major way: failure to account fully for quality change in consumable outputs. It is typically much easier to count the number of units produced than to assess intrinsic quality—especially if the desired quality may vary across customers. A significant fraction of value of quality improvements due to investments in information technology—like greater timeliness, customization, and customer service—is not directly reflected as increased industry sales, and thus is implicitly treated as nonexistent in official economic statistics.

These issues have always been a concern in the estimation of the true rate of inflation and the real output of the U.S. economy (Boskin et al., 1997). If output mismeasurement for computers was similar to output mismeasurement for previous technologies, estimates of long-term productivity trends would be unaffected (Baily and Gordon, 1988). However, there is evidence that in several specific ways,

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computers are associated with an increasing degree of mismeasurement that is likely to lead to increasing underestimates of productivity and economic growth.

The production of intangible outputs is an important consideration for information technology investments whether in the form of new products or improvements in existing products. Based on a series of surveys of information services managers conducted in 1993, 1995 and 1996, Brynjolfsson and Hitt (1997) found that customer service and sometimes other aspects of intangible output (specifically quality, convenience, and timeliness) ranked higher than cost savings as the motivation for investments in information services. Brooke (1992) found that information technology was also associated with increases in product variety.

Indeed, government data show many inexplicable changes in productivity, especially in the sectors where output is measured poorly and where changes in quality may be especially important (Griliches, 1994). Moreover, simply removing anomalous industries from the aggregate productivity growth calculation can change the estimate of U.S. productivity growth by 0.5 percent or more (Corrado and Slifman, 1999). The problems with measuring quality change and true output growth are illustrated by selected industry-level productivity growth data over different time periods, shown in Table 2. According to official government statistics, a bank today is only about 80 percent as productive as a bank in 1977; a health care facility is only 70 percent as productive and a lawyer only 65 percent as productive as they were 1977.

These statistics seem out of touch with reality. In 1977, virtually all banking was conducted via the teller windows; today, customers can access a network of 139,000 automatic teller machines (ATMs) 24 hours a day, seven days a week (Osterberg and Sterk, 1997), as well as a vastly expanded array of banking services via the Internet. The more than tripling of cash availability via ATMs required an incremental investment on the order of $10 billion compared with over $70 billion invested in physical bank branches. Computer controlled medical equipment has facilitated more successful and less invasive medical treatment. Many procedures that previously required extensive hospital stays can now be performed on an outpatient basis; instead of surgical procedures, many medical tests now use noninvasive imaging devices such as x-rays, MRI, or CT scanners. Information technology has supported the research and analysis that has led to these advances plus a wide array of improvements in medication and outpatient therapies. A lawyer today can access a much wider range of information through on-line databases and manage many more legal documents. In addition, some basic legal services, such as drafting a simple will, can now be performed without a lawyer using inexpensive software packages such as Willmaker.

One of the most important types of unmeasured benefits arises from new goods. Sales of new goods are measured in the GDP statistics as part of nominal output, although this does not capture the new consumer surplus generated by such goods, which causes them to be preferred over old goods. Moreover, the Bureau of Labor Statistics has often failed to incorporate new goods into price indices until many years after their introduction; for example, it did not incorporate the VCR into the consumer price index until 1987, about a decade after they

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Table 2
Annual (Measured) Productivity Growth for Selected Industries *(based on dividing BEA gross output by industry figures by BLS hours worked by industry for comparable sectors)*

Industry	*1948–1967*	*1967–1977*	*1977–1996*
Depository Institutions	.03%	.21%	−1.19%
Health Services	.99%	.04%	−1.81%
Legal Services	.23%	−2.01%	−2.13%

Source: Partial reproduction from Gordon (1998, Table 3).

began selling in volume. This leads the price index to miss the rapid decline in price that many new goods experience early in their product cycle. In a related example, in 1990, sales of the printed multi-volume Encyclopedia Britannica were $650 million and the production cost for each set was over $250, plus up to $500 for the salesperson's commission (Evans and Wurster, 2000). Producing a CD-ROM with the same information now costs less than $1, and presenting it via a website like www.britannica.com, costs but a fraction of that. Sales of the printed version of all encyclopedias, including Britannica, collapsed by over 80 percent in the 1990s, as the content was bundled for "free" with office software or delivered on the web. The GDP statistics captured this collapse in sales, but not the value of the content that is now free or nearly free. As a result, the inflation statistics overstate the true rise in the cost of living, and when the nominal GDP figures are adjusted using that price index, the real rate of output growth is understated (Boskin et al., 1997). The problem extends beyond new high-tech products, like personal digital assistants and web browsers. Computers enable more new goods to be developed, produced, and managed in all industries. For instance, the number of new products introduced in supermarkets has grown from 1281 in 1964, to 1831 in 1975, and then to 16,790 in 1992 (Nakamura, 1997); the data management requirements to handle so many products would have overwhelmed the computerless supermarket of earlier decades. Consumers have voted with their pocketbooks for the stores with greater product variety.

This collection of results suggests that information technology may be associated with increases in the intangible component of output, including variety, customer convenience, and service. Because it appears that the amount of unmeasured output value is increasing with computerization, this measurement problem not only creates an underestimate of output level, but also errors in measurement of output and productivity growth when compared with earlier time periods which had a smaller bias due to intangible outputs.

Just as the Bureau of Economic Analysis successfully reclassified many software expenses as investments and is making quality adjustments, perhaps we will also find ways to measure the investment component of spending on intangible organizational capital and to make appropriate adjustments for the value of all gains attributable to improved quality, variety, convenience and service. Unfortunately,

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addressing these problems can be difficult even for single firms and products, and the complexity and number of judgments required to address them at the macroeconomic level is extremely high. Moreover, because of the increasing service component of all industries (even basic manufacturing), which entails product and service innovation and intangible investments, these problems cannot be easily solved by focusing on a limited number of "hard to measure" industries—they are pervasive throughout the economy.

Meanwhile, however, firm-level studies can overcome some of the difficulties in assessing the productivity gains from information technology. For example, it is considerably easier at the firm level to make reasonable estimates of the investments in intangible organizational capital and to observe changes in organizations, while it is harder to formulate useful rules for measuring such investment at the macroeconomic level.

Firm-level studies may be less subject to aggregation error when firms make different levels of investments in computers and thus could have different capabilities for producing higher value products (Brynjolfsson and Hitt, 1996, 2000). Suppose a firm invests in information technology to improve product quality and consumers recognize and value these benefits. If other firms do not make similar investments, any difference in quality will lead to differences in the equilibrium product prices that each firm can charge. When an analysis is conducted across firms, variation in quality will contribute to differences in output and productivity and thus, will be measured as increases in the output elasticity of computers. However, when firms with high quality products and firms with low quality products are combined together in industry data (and subjected to the same quality-adjusted deflator for the industry), both the information technology investment and the difference in revenue will average out, and a lower correlation between information technology and (measured) output will be detected. Interestingly, Siegel (1997) found that the measured effect of computers on productivity was substantially increased when he used a structural equation framework to directly model the errors in production input measurement in industry-level data.

However, firm-level data can be an unreliable way to capture the social gains from improved product quality. For example, not all price differences reflect differences in product or service quality. When price differences are due to differences in market power that are not related to consumer preferences, then firm-level data will lead to inaccurate estimates of the productivity effects of information technology. Similarly, increases in quality or variety (like new product introductions in supermarkets) can be a by-product of anticompetitive product differentiation strategies, which may or may not increase total welfare. Moreover, firm-level data will not fully capture the value of quality improvements or other intangible benefits if these benefits are ubiquitous across an industry, because then there will not be any interfirm variation in quality and prices. Instead, competition will pass the gains on to consumers. In this case, firm-level data will also understate the contribution of information technology investment to social welfare.

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Conclusion

Concerns about an information technology "productivity paradox" were raised in the late 1980s. Over a decade of research since then has substantially improved our understanding of the relationship between information technology and economic performance. The firm-level studies in particular suggest that, rather than being paradoxically unproductive, computers have had an impact on economic growth that is disproportionately large compared to their share of capital stock or investment, and this impact is likely to grow further in coming years.

In particular, both case studies and econometric work point to organizational complements such as new business processes, new skills and new organizational and industry structures as a major driver of the contribution of information technology. These complementary investments, and the resulting assets, may be as much as an order of magnitude larger than the investments in the computer technology itself. However, they go largely uncounted in our national accounts, suggesting that computers have made a much larger real contribution to the economy than previously believed.

The use of firm-level data has cast a brighter light on the black box of production in the increasingly information technology-based economy. The outcome has been a better understanding of the key inputs, including complementary organizational assets, as well as the key outputs including the growing roles of new products, new services, quality, variety, timeliness and convenience. Measuring the intangible components of complementary systems will never be easy. But if researchers and business managers recognize the importance of the intangible costs and benefits of computers and undertake to evaluate them, a more precise assessment of these assets needn't be beyond computation.

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