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Beyond Computation:

Information Technology, Organizational Transformation and Business Performance

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Abstract

To understand the economic value of computers, one must broaden the definition of both the technology and its effects. Successful uses of information technology (IT) involve substantial changes in business processes, organizational structure, worker skills, product innovation and services delivered. This is particularly evident in firm-level case studies and econometric analyses which suggest that 1) organizational "investments" have a large influence on the value of IT investments and 2) among the most important benefits of IT investment are intangible, such as convenience, customer service, quality, and variety.

While the evidence of IT's contributions have often been difficult to identify in highly aggregate data, the firm-level studies have found that the output contributions of IT exceed their measured input shares. A natural explanation for the unusually high returns is the existence of unmeasured complementary inputs. Indeed, substantial changes in specific business processes and worker skills are strongly correlated with IT investments. Furthermore, the benefits of IT accrue disproportionately to the subset of firms that employ a cluster of practices involving skilled workers, delegated decision-making, and team-based production. We conclude that the case studies and broader firm-level data support the view that computers have made a contribution to business performance and economic growth that is not only large, but also disproportionate to the size of computer hardware investment alone.

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1. Introduction

How do computers contribute to business performance and economic growth? A natural place to focus would seem to be by looking at what computers do best. From their inception, computers have excelled at computation. 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. The underlying technology of computers has advanced at a breathtaking rate since the Mark I (1939) and the ENIAC (1943),[1] but even today, most people think of tasks like rapidly multiplying large numbers when asked to identify computers' strengths.

However, most problems in the world are not numerical problems. Ballistics, code breaking, parts of accounting and bits and pieces of other tasks involve lots of calculation. But the everyday work that most managers, professionals, and information workers do involves other types of thinking. If computers were only used for number crunching, their impact on the business and the economy would be fairly limited.

Fortunately, computers are not fundamentally number crunchers. They are symbol processors. We may say that digital computers can only understand everything in terms of “ones and zeros”, but that is only one way of interpreting their inner workings. The "on-off" states of digital computers and communications can just as easily be interpreted in more general, non-numeric ways, such as the "true-false" states of any formal symbol system. Because the same basic technologies can be used to organize and order any type of information that can be digitized -- numbers, text, video, music, speech, programs, and engineering drawings, to name a few -- the array of applications addressed by information technology (IT) now extends well beyond computation.[2]

[1] The Mark I was the first modern computer; the ENIAC was the first electronic computer that had no moving parts.
[2] The French word for computers, "ordinateur", comes closer capturing to this broader set of uses.

Indeed, it is difficult to find an industry that is not being significantly affected by computerization. The fundamental economic role of computers becomes clearer if one thinks about organizations and markets as information processors (Galbraith, 1977, Simon 1976, Malone and Wyner, 1996; Sah and Stiglitz, 1986; Hayek, 1945). To the extent that many of our economic institutions emerged in an era of relatively high communications costs, limited computational capability and related constraints, it is not surprising that the massive reduction in computing and communications costs has engendered a substantial restructuring of the economy. As advances in computer and communications technologies enable us to speed up more and more steps of the information processing chain, innovations in organizational technologies are needed to avoid the bottlenecks that emerge in systems that initially were designed (or evolved) to complement earlier technologies. It is the ability of IT to reduce coordination, communications and information processing costs that cause IT to have such broad economic effects.

As a result, IT is best described not as a traditional capital investment, but as a "general purpose technology" (Bresnahan and Trajtenberg, 1995). General purpose technologies have always been the source of a disproportionate share of economic growth because they not only contribute directly to greater productivity, but also contribute indirectly by enabling complementary innovations. Earlier general purpose technologies, such as the telegraph, the steam engine and the electric motor, initiated a series of complementary innovations and eventually led to dramatic productivity improvements. Some of the complementary innovations were purely technological, such as "wireless" version of telegraphy developed by Marconi. However, some of the most interesting and productive developments were organizational innovations. For example, a major effect of the telegraph was to facilitate the formation of geographically dispersed enterprises (Milgrom and Roberts, 1992). Similarly, the electric motor permitted more flexibility in the placement of machinery in factories, thus enabling industrial engineers to improve manufacturing productivity dramatically by redesigning workflow (David, 1990). The steam engine was at the root of a whole cluster of changes that helped ignite the first industrial revolution. In all these cases, the economic contributions of these technologies were substantially larger than would have been predicted by examining the quantity of capital investment devoted to them, because the vast majority of the benefits are due to the complementary innovations they enable.

In this paper we will argue that, like earlier general purpose technologies, much of the economic value of IT is related to the ability of computers to enable complementary innovations is business processes and work practices across a range of functions and industries. These innovations, in turn, lead to productivity increases not only because they reduce cost, but also because they enable firms to increase output quality in the form of new products or in improvements in intangible aspects of existing products (convenience, timeliness, quality, variety). We present a variety of empirical evidence to support this story:

- First, case studies link investments in IT with substantial transformation in firms' internal organization, their supply chains, and their customer relationships, including the products and services provided. (Section 2)
- Second, firm-level statistical evidence reveals a relationship between IT investments and higher productivity levels, increased productivity growth, and larger stock market valuations. (Section 3.1)
- Third, these studies also reveal a pattern of results consistent with the existence of organizational complements. Specifically, unless one posits the existence of large intangible correlates to IT, there appear to be substantial "excess returns" to IT, both in terms of productivity effects and stock market valuations, in firm-level studies. (Section 3.2)
- Fourth, several studies have directly measured organizational changes in decision rights, promotion and incentive systems, worker skills, firm boundaries, and other measures of internal organization. These studies find that such changes are in fact broadly correlated with IT investment and/or use. (Section 3.3.1)
- Fifth, firms which combine IT investments with the most common types of recent organizational changes appear to have higher productivity levels and stock market valuations than firms which invest in IT without the corresponding organizational changes or vice versa. (Section 3.3.2)

- Sixth, IT investments are concentrated in poorly measured sectors of the economy, and more importantly, managers report that the main benefits of IT are in poorly measured components of output such as quality, variety, timeliness, convenience, and customer service. (Section 4)

This story of IT and organizational complements has a number of implications for both understanding the long-run contribution of computers to economic welfare, as well understanding how different approaches to measure this contribution are likely to perform. First, the economic effect of computers is likely to be much larger than the magnitude implied by the total capital investment in computers. This is because much of the "investment" entailed by computerization is in workforce reskilling, organizational redesign, firm restructuring, and other large scale organizational changes, which can easily dwarf the size of computer investment. As such, recent analyses that suggest a large contribution of computers to economic growth (Jorgenson and Stiroh, 2000; Oliner and Sichel, 2000) may actually *understate* the actual contribution of computers. Second, the ability of individual firms to capture the benefits of computers is heavily determined by their ability to make complex and often painful organizational changes – in the short term, this can yield substantial rents to firms that are able (or willing) to make these changes. However, since imitation of computer-enabled innovations is rampant, it is likely that much of benefit of innovation will spill over to competitors and ultimately customers within a few years.

In terms of measurement issues, our story also suggests that the benefits of computer investment are difficult to assess using traditional approaches for growth and productivity accounting, and that equivocal evidence on the benefits of computers in some previous empirical studies reflects these difficulties. While computers enable firms such as Dell, Wal-mart or Capital One Financial to change the way they do business (detailed in the case study section to follow), much of the resulting innovation in quality and customer service goes uncounted in standard economy- or industry-level productivity calculations. While saving customer time, raising service quality levels and creating new products create substantial welfare gains to the economy, these benefits are largely ignored in our standard measures of economic performance (see e.g., Boskin et. al., 1997). As a result, the contributions of computer investment are likely to be systematically understated by aggregate level analyses, but may be better measured at the firm-level where improvements in output quality might be partially reflected in higher sales, and thus, will be observable. In addition, if the benefits of computers are primarily realized in conjunction with complementary investments, which typically are created at the firm-level, it may be difficult to observe the effects of computers without using micro-level data. These difficulties may reflect why contributions of IT to firm-level productivity were evident in studies as early as 1993, while most of the positive macroeconomic evidence is very recent.[3,4]

In the following sections, we review the evidence on the effects of computers on economic performance, with emphasis on studies conducted at the firm-level (where we have focused our own research efforts). We then explore the implications of results for assessing the contribution of IT to overall economic growth, linking the firm level evidence to evidence from more aggregate data. While there are strengths and weaknesses in all the individual studies we consider, collectively they paint a coherent picture: organizational innovations play a critical role in realizing value from IT and that IT and its complements play a major role in economic growth by creating improvements in output quality.

2. Case Examples

There are numerous examples of how companies have employed IT to change the way they conduct business either internally or externally. A common theme throughout these cases is that investment in IT is *complementary* to changes in other aspects of the organization. Complementarity exists when increasing the quantity of one factor raises the marginal benefit of another factor. This would suggest that complementary factors will tend to appear together (Milgrom and Roberts, 1990; Holmstrom and Milgrom, 1994) in "systems" or "clusters" rather

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[3] Studies that have estimated the macroeconomic contribution of computers, and found large (>.3% output growth per year) effects are Gordon (1999), Jorgenson and Stiroh (2000) and Oliner and Sichel (2000). However, Bresnahan (1986) and Brynjolfsson (1994) had previously found large consumer surplus contributions of investments in computers, and Lau and Tokutsu (1992) found a substantial contribution using a growth accounting approach based on a macroeconomic cost function. All of these studies, however, infer the contribution of IT by applying a standard rate of return (implied by cost minimization) and multiplying it by investment or in the case of Gordon (1999), output levels.

[4] For a more general treatment of the literature on IT value see reviews by Attewell and Rule (1984); Brynjolfsson (1993); Wilson (1995) and Brynjolfsson and Yang (1996).

than being used in isolation. A further implication is that if there is some experimentation, accidents, differences in capabilities, or other reasons for variation in adoption of these practices, firms that adopt the entire complementary system together will typically show the greatest performance.

These arguments also have implications in understanding the resistance to or difficulty of implementing IT-enabled organizational change. Even when a new system of practices is substantially more productive than an existing system, changing incrementally (one factor at a time) from one complementary system to another can often make the firm substantially worse off than retaining the old system, at least until the firm has completed the transition (e.g. Brynjolfsson, Renshaw, and van Alstyne, 1997). The idea that changes between complementary systems must be "all or nothing" was part of the logic that was behind the organizational reengineering wave of the 1990s, hence the slogan "Don't Automate, Obliterate" (Hammer, 1990). It also suggests a reason for the reportedly high failure rate of reengineering and other large scale IT implementations (Kemerer and Sosa, 1991) and why only 30% of managers surveyed believed the failure rate of large scale IT projects was declining from 1985 to 1995 despite more experience with IT projects, better technologies, and improved project management techniques (Standish Group, 1995).

Many of the organizational practices that have been successful over the last century and have persisted even today are a direct result of the high cost of information processing. For example, hierarchical structures are known to be efficient at minimizing communications costs (Malone, 1987; Radner, 1993; Radner and Van Zandt, 1992). Producing simple, standardized products is the most efficient way to utilize scale-intensive and inflexible manufacturing technology. However, as the cost of automated information processing has fallen over 6000-fold since the 1960s, it is unlikely that the work practices that emerged in the previous era also happen to be the same practices that best leverage the value of cheap information and flexible production. Indeed, 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 IT.

More broadly, a variety of industries have been transformed in fundamental ways by combining information technology with changes in strategy, firm structure, or work practices. In this section we will discuss the case evidence on three aspects of this transformation: the transformation of the firm, the transformation of supplier relations, and the transformation of the customer relationship.

2.1. Transforming the Firm

The need to match organizational structure to technology capabilities and the challenges of making the transition to an IT-intensive production process is concisely illustrated by a case study of "MacroMed", 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. These investments also coincided with a management edict for sweeping changes in incentive systems (the elimination of piece rates), job responsibilities (workers gained authority for scheduling machines, identifying process innovations and for dealing more closely with customers and suppliers), information flows (increased lateral communication and teamwork) and literally dozens of other organizational practices. Despite the recognition by management that a complete system of changes needed to be implemented as well as the use of a detailed implementation plan, the new system initially fell well short of their expectations for greater flexibility and responsiveness.

Further investigation revealed that line workers still retained many elements of the now-obsolete old work practices. Typically, this did not reflect any conscious effort to undermine the change effort. On the contrary, the workers understood which practices were important for success in the past and sought to apply this knowledge. For example, one worker explained that "the key to productivity is to avoid stopping the machine for product changeovers." While this was a valuable heuristic with the old equipment, it negated the flexibility of the new machines and created large work-in-process inventories. Ironically, the new equipment was so flexible that the workers succeeded in getting it to work much like the old machines!

Eventually, management concluded that the best approach was to introduce the new equipment in a "greenfield" site with a handpicked set of young, motivated employees who were relatively unencumbered by knowledge of the old practices. This approach succeeded and, while a number of unanticipated "bugs" in the new workflow needed to be worked out, major performance improvements ultimately materialized. The benefits of the new system – and the difficulties in achieving them – were large enough that management ordered all the factory windows painted black to prevent potential competitors from seeing the system in action.

Other types of systems investments also show strong complementarities with some aspects of internal organization. For example, in consulting firms the implementation of "knowledge management" systems, designed to capture and share expertise throughout the firm, has often met with substantial resistance until incentives and other organizational practices were changed to support the use of the system. Consultants who are rewarded for knowing things that no one else in the firm knows are usually not eager to share their expertise with coworkers via an electronic knowledgebase, especially in competitive “up or out” organizations (Orlikowski, 1992; McKinsey and Company, 1994; KPMG, 1998). In addition, the cost of making these organizational changes can be substantial. For every dollar an organization spends on implementing enterprise resource planning software (ERP) such as SAP R/3, the firm typically spends $3-5 on consultants to integrate the system into the organization, and a similar amount on internal expenses such as retraining, designing new business processes, and managing the implementation.

2.2. Changing Interactions with Suppliers

Historically, due to a lack of efficient supply markets and difficulty in coordinating with external suppliers, large firms tended to produce many of their required inputs in-house. Recently many of these firms are finding that the benefits of vertical integration are outweighed by the disadvantages of internal production such as an inability to realize economies of scale or specialization, agency costs arising from a lack of market discipline, and inflexibility leading to late adoption of new production processes. Even companies whose success was tied to vertical integration, such as General Motors, have since reversed course, divesting large internal suppliers. As one industry analyst 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).

One of the earliest forms of IT-enabled interorganizational communication is electronic data interchange (EDI). Through a standard format, firms can place orders and receive confirmations from suppliers. This saves the cost of preparation and transmittal of paper purchase requests and invoices and enables ordering systems to be tied directly to production systems eliminating costly, time consuming, and error prone manual data entry (Johnston and Vitale, 1988). Although the cost savings from adopting EDI can be large, even greater savings can be achieved when EDI is combined with other methods of supply chain optimization.

A particularly successful early example of an interorganizational system is the Baxter ASAP system, which enables hospitals to order supplies directly from wholesalers (Vitale and Konsynski, 1988; Short, 1992). Originally, the system was envisioned as a way of reducing data entry cost for the 40,000 + purchase orders per year that Baxter's field sales representatives completed by hand for each hospital they served. However, once ordering was computerized and data were available on levels of hospital stock, Baxter increasingly took responsibility for the entire supply operation -- designing stock room space, setting up computer-based inventory systems, and providing entirely automated inventory replenishment. The combination of the technology and the new supply chain organization created substantial efficiency gains both for Baxter (no paper invoices, predictable order flow) and for the hospitals (elimination of stockroom management tasks, inventory optimization, and reduction of stockouts). The later versions of the ASAP system also included the facility to order from other suppliers, creating an electronic marketplace in hospital supplies.

One of the most sophisticated and modern examples of computer-based supply chain integration is present in consumer packaged goods. Traditionally, sales of products such as soap and laundry detergent were heavily driven by off-invoice promotions, in which manufacturers offered discounts, rebates, or even cash payments to *retailers* to stock and sell their products.[5]

[5] This is above and beyond the costs of direct promotions to consumers through couponing and advertising.

These promotions often created substantial production inefficiencies. Because many consumer products can be warehoused for considerable periods of time without deterioration, retailers tended to make massive purchases during promotional periods (a practice known as "forward buying") increasing volatility in manufacturing schedules and increasing costs (e.g., rush orders for inputs, inefficient production run length). In response to the problem of forward buying, manufacturers increased the speed of packaging changes (thus enabling older product to be easily identified) and developed internal audit departments which monitored retailers' purchasing behavior to detect contractual abuse – both examples of pure deadweight loss. Moreover, manufacturers who relied on sales data for planning received a distorted picture of the final demand characteristics of their markets, a problem exacerbated by retailers' tendencies to guard consumer data closely to improve their bargaining position with manufacturers (see Clemons, 1993, for a discussion of the problems that promotion-based selling creates for manufacturers).

To eliminate these efficiencies, Procter and Gamble (P&G) pioneered a program called efficient consumer response (ECR). Implementing ECR requires changes in a whole collection of work practices, information systems and other aspects of the retailer-manufacturer relationship. These include direct transmission of retailers' checkout scanner data to the manufacturer, fully automated ordering through EDI, automated payments and invoicing, elimination of off-invoice promotions and a shift to "everyday low price" (EDLP) pricing, and continuous replenishment of products on a daily basis. Manufacturers also became increasingly involved in inventory decisions and began a move toward "category management", where a lead manufacturer would take responsibility for an entire retail category (e.g. laundry products) determining stocking levels for their own and other manufacturers products as well as complementary items.

This collection of changes reduced substantially the operational costs for both manufacturers and retailers and also removed the incentive distortions that created many of the inefficiencies in the first place. Since there were large efficiency gains from this system, manufacturers could offer retailers substantially lower prices to induce them to share data. Consumers especially benefited from the improved understanding manufacturers gained regarding their tastes and preferences and the resulting increase in product variety, convenience and innovation. Computers were a critical component of this new form of supply chain organization. In particular, without the direct computer-computer links to scanner data and the electronic transfer of payments and invoices there would be no way to have the levels of speed and accuracy needed to implement such a system.

Due to recent technological innovations related to the commercialization of the Internet, such as standardized data interchange languages such as XML and off-the-shelf, internet-based supply chain management software, the cost of building electronic supply chain links has decreased dramatically leading to an accelerated rate of supply chain restructuring. Some analysts estimate that across different industries, computer-based procurement systems could lead to reduction of inputs costs ranging from 10-40% (Forrester, 1999). While some of these savings represent a redistribution of bargaining power from suppliers to customers which may have little net effect on overall economic output, a reduction in delay time for materials procurement, reduced inventories, reduced paper handling costs, improved information flow regarding customer preferences and supplier costs, ability to handle greater product variety, and the removal of price distortions that arise from problems such as double marginalization lead to a first order improvements in productivity. In addition, improvements in interorganizational communication, supplier selection and monitoring has led to a much greater reliance on subcontracting, outsourcing and buyer-supplier partnerships, enabling production efficiencies of scale, scope and specialization to be realized without the attendant transaction costs of market governance.

2.3. Changing Customer Relationships

Even in seemingly mature industries with massive overcapacity, some companies have managed to use information, information technology, and organizational innovation to deliver greater value for the customer while earning extraordinary profits. Capital One Financial Corporation, previously the credit card division of Signet Bank, was formed to exploit the fact that most credit card issuers offered inflexible standardized pricing to all of their customers, despite the problem that this generated enormous variations in customer profitability (Clemons and Thatcher, 1997). Low cost customers were effectively being overcharged to subsidize unprofitable accounts, creating opportunities for private gains through price discrimination as well as social welfare increases as large customer segments were newly able to access credit markets on terms that reflected their risk-adjusted cost. This opportunity went unrecognized for many years, primarily because the information systems infrastructure in place at most credit card issuers was directed at minimizing processing cost, not identifying the factors that affect profitability. Furthermore, these systems were often too inflexible to offer customized terms to specific customers.

Through a strategy called "test and learn", Signet Bank offered a wide range of product designs (e.g., annual fees, security deposit, interest rate, rebates, etc.) to different subsets of potential customers identified through publicly available sources. Through these experiments, some of which proved to be quite costly, they amassed an enormous database that related observable customer characteristics, product choice, and long-term customer profitability. Using these data, they identified several highly profitable product designs that were then aggressively promoted to a suitable target group.[6]

In addition to having large databases and flexible systems that allow analysis of ongoing customer information, they also support the use of this information with a skilled staff and organizational innovation. They claim to employ more Ph.D.s in their firm than the rest of the credit card industry combined. In their telephone support area, skilled customer representatives are empowered to negotiate product features with customers, supported by data on the impact of changes on customer profitability, and incentives based on the future value of accounts they retain. Competitors who lack the systems or the staff to implement these programs are at a severe disadvantage. In the four years following its spinoff from Signet Bank, the price of Capital One stock rose over 5-fold. Meanwhile, some large, previously successful card issuers such as AT&T have left the business, and other issuers who lack the ability to micro-segment the market are under substantial profit pressure.

However, over the long run this advantage has been substantially reduced as competitors imitated successful product designs and retooled their systems to enable flexible pricing and data

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[6] For example, they created a balance transfer card that offered lower interest rates to customers who transfer a large existing credit balance. This product accomplishes a form of second-degree price discrimination to identify high profitability "revolvers", customers who borrow large sums on credit cards but pay back slowly. The lower interest rate is not attractive to customers who do not intend ever to pay since some effort is required to transfer a balance. The lower rate is also not attractive to "transactors" who pay off their balances in full every month and tend to also

mining, often procuring this software from third party vendors who now incorporate these features in standard off-the-shelf packages. Capital One, recognizing that much of the advantage in credit cards has been already "played out", moved to other industries that have similar characteristics such as the resale of long-distance and cellular telephone service. Again, competitors in these industries have also imitated successful products eroding the profitability of their price discrimination strategy. The ability of Capital One to sustain their higher than average earnings growth is dependent on continually finding new markets to apply their core "technology" of differential pricing and data-driven account maintenance.

In addition to IT innovations in operational systems leading to dramatic improvements in customer service, convenience or product variety, the Internet has opened up a new range of possibilities for enriching interactions with customers. Dell Computer has had enormous success in attracting incremental customer orders and improving service by placing configuration, ordering, and technical support capabilities on the world wide web (see www.dell.com). This change in the front end was coupled 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. This transformation of the traditional build-to-stock model of selling computers through retail stores to a consumer driven build-to-order model has been estimated to give Dell as much as a 10% cost advantage over their rivals in production cost and erects a substantial barrier to entry to other firms which would like to imitate Dell. Buying web-based storefront technology to match Dell's (which is now available from a number of firms) would only be the tip of a much larger iceberg of organizational investments.

2.4. Summary

The case evidence suggests that successful IT investment is often coupled with redesign of internal organization, a shift in how firms interact with suppliers, and the pursuit of new sources of value for customers such as service, variety or convenience. In the short run, these innovations create substantial private value to the innovators. However, in most of the cases

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be unprofitable. Thus, the lower rate for transfers attracts customers with relatively low operations cost but very high interest-accruing balances -- the most profitable segment of the business.

cited above, imitation by both competitors as well as third party vendors, has created substantial technological spillovers to the rest of the industry, creating further gains in consumer surplus as rents get redistributed from the firms to consumers. In all these cases discussed, it is not merely the idea that IT lowers the cost of conducting business as usual through automation, nor a "silver bullet" solution where the technology alone creates the value, but the collection of organizational, strategy, and systems changes that lead to substantial productivity gains. The managers involved clearly recognized that the costs of these complementary changes typically dwarf the direct IT costs. To the extent that such collections of changes create lasting value, they behave more like investments than expenses.

3. Large-sample Empirical Evidence on IT, Organization and Productivity

While the case evidence provides many examples of a strong link between the value of information technology and investments in complementary organizational practices, it is difficult to know how general these effects are. Do the cases we describe represent the idiosyncratic situations of a few "leading edge" firms, or are the lessons more widely applicable? To understand general trends, it is necessary to examine these effects across a wide range of firms and industries. In this section we will explore the results from large-sample statistical analysis. First, we examine studies that focused on the direct relationship between IT investment and business value to understand the general impact of computers on performance as well as to provide some indirect evidence of complementary factors. We then consider studies that directly measured these organizational factors and their correlation with IT use, as well as the few initial studies that have linked this relationship to productivity increases.

3.1. IT and Productivity

Much of the early work on the relationship between technology and productivity utilized economy-level or sector-level data and found little evidence of a relationship. For example, an analysis by Steven Roach (1987) showed that while computer investment per white-collar worker in the service sector rose several hundred percent from 1977-1989, there was no discernable increase in output per worker as conventionally measured. Using Bureau of

Economic Analysis data for manufacturing industries at the 2-digit SIC level from 1973-1986, Morrison and Berndt (1990) showed that the gross marginal product of "high tech capital" (principally computers) was approximately $0.80 per dollar of investment, implying a –20% rate of return. Using the same data, Berndt and Morrison (1992) concluded that the relationship between high-tech investment and output was, at best, mixed and inconclusive, and that in many industries these supposedly labor-saving investments were associated with an *increase* in labor demand. Similar results were found by Morrison (1997), who utilized somewhat more structured models and extended the dataset to cover a time period ending in 1991. The results of these studies were summarized (and in some cases predicted) by Robert Solow (1987) who remarked, "you can see the computer age everywhere except in the productivity statistics."

However, as early as 1993, analyses at the firm level were beginning to find evidence of a substantial effect of computers on productivity levels of firms. Using data from over 300 large firms over multiple years (1988-1992), Brynjolfsson and Hitt (1993, 1996) and Lichtenberg (1995) estimated production functions (F) that relate the amount of output that a firm produces to the inputs it consumes and variables identifying the firm (i), industry (j) or time (t):

$$Q_{it} = F(K_{it}, L_{it}, M_{it}, C_{it}, S_{it}; i, j, t)$$

where Q is a measure of output or value added, K is ordinary capital, L is non-IT labor, C is computer capital and S is IT labor.

Assuming a standard form (Cobb-Douglas) for the production function F(·) and taking logarithms yields the following estimating equation:[7]

$$\log Q_{it} = \log A(i, j, t) + \alpha_k \log K_{it} + \alpha_l \log L_{it} + \alpha_m \log M_{it} + \alpha_c \log C_{it} + \alpha_s \log S_{it} + \varepsilon_{it}$$

where: A(·) generally includes dummy variables for time and industry or firm

The coefficients of interest in these models are α_c and α_s which represent the output elasticity of computer capital and IS labor respectively. Brynjolfsson and Hitt and Lichtenberg found both of these elasticities were positive and significant. Estimates of the elasticity of computer capital range from .01-.04 by Brynjolfsson and Hitt (1993, 1996) to .10 by Lichtenberg (1995) when total output is used as the dependent variable. This relationship is summarized in Figure 1, where we compare firm level IT investment against multifactor productivity (excluding computers) for the firms in the Brynjolfsson and Hitt (1993) dataset over 1987-1992. These values appear to exceed the (measured) input share of IT, suggesting abnormally high returns to investors or the existence of unmeasured costs or barriers to investment. Estimates of the contribution of IS labor range from slightly over a dollar to six dollars for every dollar invested. Dewan and Min (1997) and others (e.g., Rai, Patnayakuni, Patnayakuni, 1997) corroborated these results using similar data and methods.

Several studies have also examined the returns to IT 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 uncover a relationship between a firm's productivity and the fraction of its employees who report using a PC at work. Although they only observe a small subset of the employees of any given firm, they use econometric techniques to calculate the true estimate of the elasticity of computers by comparing the results of firms that have different numbers of reported employees in the data. Their estimates are similar to earlier estimates of the computer elasticity.

Other studies have also been conducted at a more micro-level and corroborate these firm level studies. These studies generally use measures of technology use, rather than investment quantity, and tend to focus on the effects of mechanization rather than the output contributions of general purpose computing.

Kelley (1996) found that metalworking plants that use computer-controlled machinery are substantially more productive than other metalworking plants. Black and Lynch (1997) used data on the percentage of employees who use computers and related this to plant productivity; they found that the contribution of computers was positive and significant. Doms, Dunne and

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[7] In general, using different functional forms, such as the transcendental logarithmic (translog) production function, has little effect on the measurement of output elasticities. The standard method of estimation is to include dummy

Troske (1997) utilized data on the adoption of different numbers of advanced manufacturing technologies (AMTs) and found that plants that use more AMTs (many of which are computer-based) had higher productivity and wages. Other studies have shown similar results at even finer levels of detail; for example, computerization has been found to increase productivity in government activities such as toll collection and postal sorting (Muhkopadhyay, Rajiv and Srinivasan, 1997; Muhkopadhyay, Lerch and Mangal, 1997; see also Lichtenberg, 1998 for a study of the productivity of IT across multiple government organizations).

There are weaknesses in each of these studies, especially when it comes to establishing causality.[8] However, taken collectively, the studies suggest that IT has a substantial contribution to output when measured directly, even during time periods where aggregate analyses have been inconclusive.

3.2. Indirect Evidence of Organizational Complements from Productivity Studies

While these studies did not explicitly measure organizational assets separate from IT investment, there are a number of inferences that can be made about the relationship between IT and organizations from these productivity studies. Most of the firm-level studies that examined the relationship between IT and productivity show that the net benefits of computers, after capital costs were subtracted, were substantially greater than zero in both economic and statistical significance. Because economic theory would predict that the net benefits of any investment, including IT, should be zero in equilibrium (absent market imperfections or barriers preventing the adoption or diffusion of IT), the evidence of "excess returns" requires further exploration.

One explanation is that the output elasticities for IT are about right, but that we are underestimating the input quantities. This would lead to an overestimation of the rate of return

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variables for time and industry as indicators of multifactor productivity (A).

[8] Perhaps instead of IT causing greater output, firms with unexpectedly high sales disproportionately spend their windfall on computers. However, attempts to correct for this bias using various techniques (such as including only the predetermined components of inputs or various instrumental variables) typically further increase the estimated IT coefficients (see e.g. Brynjolfsson and Hitt, 1996; Brynjolfsson and Hitt, 1998). Thus, if reverse causality is a problem, it may be better explained by IT investment being *less* procyclical than other types of investments. That is, firms with an unexpected increase in free cash flow invest in other factors, such as labor, before they change their IT spending.

for IT. If computers are associated with unmeasured complementary investments, then the correlation between output and IT may in part reflect the contributions of other complementary factors. Dividing the output of the whole set of complements by only the factor share of IT will imply disproportionately high rate of return for IT. Thus, the presence of unmeasured, complementary organizational investments may explain a substantial portion of the excess returns (a more formal analysis of this issue appears in Hitt (1996) and Brynjolfsson and Hitt (1998)).

There is a variety of other evidence that "hidden assets" play an important role in the relationship between IT and productivity. Utilizing similar data to previous work, Brynjolfsson and Hitt (1995) estimated a firm effects productivity model (with a more general transcendental logarithmic productivity specification). This regression method can be interpreted as dividing firm-level IT benefits into two parts: a part due to variation in firms' IT investments over time, and a part due to relatively invariant firm characteristics. In this specification, Brynjolfsson and Hitt found that, the coefficient on IT was reduced by about 50% as compared to the results of an ordinary least squares (OLS) regression, while the coefficients on the other factors, capital and labor, were only slightly changed. This change suggests that unmeasured and slowly changing organizational practices (the "fixed effect") significantly affect the returns to IT investment.

Using different data, which included more firms (600+) and a longer time series (1987-1994), Brynjolfsson and Hitt (2000) examined the effects of IT on productivity growth rather than productivity levels, which had been the emphasis of most previous work. Their most striking result is that the effects of IT are substantially larger when measured over longer time periods. When one-year differences in IT are compared to one-year differences in firm productivity, the measured benefits of computers are approximately equal to their measured costs. However, in a variety of econometric specifications, the measured benefits rise by a factor of 2-8 as longer time periods are considered. One interpretation of these results is that the benefits of IT are increased over time because organizational complements are not always present at exactly the moment that IT investments come on-line. The short-term returns represent the direct effects of IT investment, while the longer-term returns represent the effects of IT when combined with related investments in organizational change. Further analysis suggested (based on earlier results by Schankermann

(1986) in the R&D context) that these omitted factors were not simply IT investments that were erroneously misclassified in capital or labor. Instead, the omitted factors had to have been accumulated primarily over previous time periods in ways that would not appear on the current balance sheet. Firm-specific human capital or "organizational capital" would fit this description.[9]

Another perspective on the value of these organizational complements to IT can be found using financial market data, drawing on the literature on the empirical measurement of Tobin's q. These models relate the stock market value of the firm to the various capital assets it owns. The basic assumption underlying these analyses is that in equilibrium the market value of a firm, as measured by the stock market, should be equal to the sum of the values of its fixed assets. Typically, this has been employed to measure the relative value of different types of observable assets such as R&D or physical plant. However, as suggested by R. Hall (1999a), Tobin's q provides a reasonable measure of the true "quantity" of capital, especially when some of the components are not otherwise observable.[10] Hall specifically argues that Tobin's q is useful for considering the value of "technology, organization, business practices, and other produced elements of successful modern corporation" (R. Hall, 1999b).

Using these models and a variety of econometric techniques, Brynjolfsson and Yang (1997) found that while a dollar of ordinary capital is valued at approximately a dollar by the financial markets, a dollar of IT capital appears to be correlated with between $5 and $20 of additional stock market value for the firm. An explanation for these results is that IT capital is disproportionately associated with other intangible assets that affect firm valuation but do not appear on the balance sheet as a capital asset.[11] For example, the cost 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 represent investments that have long term benefits (at least in expectation!), yet go uncounted in firm financial statements.

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[9] Part of the difference in coefficients between short and long difference specifications could also be explained by measurement error (which tends to average out somewhat 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).

[10] This is formally stated in Hall's "Quantity Revelation Theorem".

In this interpretation, for every dollar of IT investment, the firm also has between $4 and $19 of additional intangible assets. A related explanation is that substantial "adjustment costs" must be incurred before IT is effective. These adjustment costs drive a wedge between the value of a computer sitting on the loading dock and one that is fully integrated into the organization.

Combining the productivity and Tobin's q analyses, we gain some insights into the properties of IT-related intangible assets even if we are not able to measure these assets directly. They are large in the sense of potentially being several multiples of the measured IT investment. They are unmeasured in the sense that they do not appear as a capital asset or as another component of firm input, although they do appear to be unique characteristics of particular firms (as opposed to industry effects). Finally, their effect is greater in the long term than the short term, suggesting that multiple years of adaptation and investment is required before their influence is maximized.

3.3. Direct Measurement of the Interrelationship between IT and Organization

In this section we consider studies which directly attempted to measure organizational complements to IT. If indeed there exist other types of organizational investments that are complementary to IT investment, then this implies two possible observable conditions. First, these factors are likely to be correlated with increased IT investment in a sample of firms. Second, firms that combine complementary factors (e.g. IT and certain organizational practices) should have higher performance than firms that adopt one but not the other (see Holmstrom and Milgrom, 1994, and Athey and Stern, 1997, for a discussion of the empirical assessment of complementarities relationships).

Measuring these output effects in practices is only possible if there is some source of exogenous variation due to external factors or firm mistakes. If there are no barriers to adopting the optimal level of all factors immediately and all firms face the same cost and benefit drivers of IT investment and organizational practices, then there will be no data variation: all firms will immediately adopt the same, optimal set of practices. If either of these conditions is relaxed,

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[11] Note that the simple explanation that IT capital is simply worth more than other types of capital would be inconsistent with economic rationality.

then different firms will adopt different levels of the various practices and may show differences in productivity. This could arise if some managers do not fully understand all the complementarities, if some firms make mistakes in their adoption levels, if some firms face adjustment costs or other barriers preventing them from optimizing, or if work practice adoption is partially random, due to chance or conscious experimentation.

In such cases, we may be able to observe both correlations between the use of various complementary factors of production and productivity differences between firms that adopt the complementary system as a whole and those that adopt practices piecemeal (e.g. IT investment without organizational redesign or vice-versa). However, without a full structural model specifying both the production relationships as well as the demand drivers for each factor, statistical methods alone cannot prove that these practices are indeed complements (see more discussion of this issue in Athey and Stern, 1997) when there is not a clear alternative hypothesis. However, description and refutation of possible alternative explanations can often leave complementarities as the most plausible explanation for observed relationships between IT and organizational factors (see Bresnahan, Brynjolfsson and Hitt, 1998 for an example in the context of investigating IT-skill complementarities).

3.3.1. Correlational Results

Hitt and Brynjolfsson (1997) surveyed approximately 400 large firms to obtain information on several aspects of internal organizational structure: allocation of decision rights, workforce composition, and investments in human capital. Across a wide variety of measures of information technology, they find that greater levels of IT are associated with increased delegation of authority to individuals and teams, greater levels of skill and education in the workforce, and an increased emphasis on pre-employment screening for education and training. In addition, they find that these individual work practices are themselves correlated with each other, suggesting that they do not act independently but are part of an overall complementary work system. Adopting a more structured demand framework, Bresnahan, Brynjolfsson and Hitt (1998) also found that firms that adopt this work system have a higher demand for IT.

Overall, these results show a consistent pattern that IT investment is greater in organizations that are decentralized and have a greater level or demand for human capital in the workforce. Some other studies have also considered the relationship between work organization and IT use. Kelley (1994) finds that the use of programmable manufacturing equipment is correlated with several aspects of human resource practices. Although the interaction of organizational practices and IT was not often the focus, evidence in many of the IT-productivity studies conducted at a micro-level (see e.g. Muhkadopadhyay et. al., 1995 and Black and Lynch, 1997) suggests that the influence of IT on productivity is affected by various measures of worker characteristics or work organization.

The human capital results are also corroborated by industry-level studies on the demand for skills and education. Berndt, Morrison and Rosenblum (1992) found that high IT firms had a greater demand for education and skilled workers in data on 2-digit manufacturing industries. Berman, Bound and Griliches (1994) discovered that computer using industries tended to have a greater demand for skilled workers. Autor, Katz and Krueger (1997) found that high-IT industries had faster growth in the share in the proportion of college educated workers they employed than other industries. Similar results were found by Brynjolfsson, Bresnahan and Hitt (1998) at the firm level when they examined the relationship between IT use and demand for skills; firms that had high levels of IT use also tended to invest more in training and screening for education. Again, this is consistent with the idea that increasing use of computers is associated with a greater demand for human capital.

Several studies have also considered the effect of IT on macro-organizational structure such as firm size, vertical integration, and diversification. Brynjolfsson, Gurbaxani, Malone and Kambil (1994) found that increases in the level of IT capital in an economic sector were associated with a decline in average firm size in that sector. In addition, these effects were most pronounced after a two-year lag. They argue that this is consistent with IT leading to a reduction in vertical integration. Hitt (1999) analyzed firm-level data and examined the relationship between IT capital stock and direct measures of firm's participation in multiple industries: vertical integration and diversification. He found that IT was strongly correlated with decreased vertical integration, as well as a small correlation with increased diversification. These corroborate earlier case analyses and theoretical arguments (Malone, Yates and Benjamin, 1987; Gurbaxani and Whang, 1991; Clemons and Row, 1991; Clemons, Reddi and Row, 1993) that suggested that IT would be associated with a decrease in vertical integration and a shift toward market governance as a result of the lower costs of coordinating externally with suppliers engendered by IT.

Altogether, these studies are consistent with the idea that IT is complementary to certain types of organizational characteristics; firms that use more computers (broadly defined) tend to delegate more decision making to individuals and teams, have higher skilled staff, invest more in training and education, and adopt corporate structures that involve less vertical integration. However, while this is consistent with complementarities, it may also be due to other effects. For example, suppose that some firms have a tendency to overspend on both organizational and technological innovation: they adopt new ideas without a thorough economic justification. This could lead IT and "modern" work organization to be correlated even it they were not complements. To distinguish spurious correlations from combinations of factors motivated by economic concerns, it is useful to perform productivity analyses. If combining IT with these types of organizations is economically justified, then firms that adopt these practices as a system should outperform those that fail to combine IT investment with appropriate organizational structures.

3.3.2. Productivity Effects of Combining IT and Organizations

Firms that adopt the previously identified work practices and organizational structures have a higher contribution of IT to productivity (Bresnahan, Brynjolfsson and Hitt, 1998). For example, firms that are in the top quartile of decentralization (as measured by an index of organizational practices), have a 25% greater IT elasticity and a 20% greater investment in IT. These results hold true whether organizational practices are measured as a scale of organizational variables or whether they are identified by a single indicator, the adoption of "self-directed work teams”. The data also show that firms that are in the top half of both IT investment and decentralization are on average 5% more productive than firms that adopt only IT or only the decentralized organization.

Similar results also appear when performance is measured as stock market valuation. As hypothesized earlier, organizational decentralization does behave as an intangible asset: firms that are in the top third of decentralization have a 6% higher market value after controlling for the levels of all other measured assets. Moreover, a dollar of IT capital is valued between $2 and $5 more in decentralized firms than centralized firms (Brynjolfsson, Hitt and Yang, 1998; 2000). In addition, this relationship is particularly notable for firms that are both high-IT and highly decentralized, although low-IT, centralized firms also appear to have slightly higher benefits than the average, also consistent with complementarities (Figure 2). This supports two elements of our previous argument; first, that organization is indeed an asset with a positive value (or at least a positive cost), and second, that these types of organizations increase the value of IT investment.

These results are consistent with the collection of previous case and empirical work. These types of organizational practices may represent at least one component of an overall system of IT-enabled work practices, although there are undoubtedly others yet to be identified in future work.

4. Intangible Outputs and the Divergence of Firm-Level and Aggregate Studies

One of the most serious problems in productivity measurement is accurately accounting for quality change. It is typically much easier to count the number of units produced by a firm than to assess their intrinsic quality. Harder still is knowing whether the product is delivered to the specific customer who values it most. As a result, a significant fraction of value of quality improvements, greater timeliness, customization, and customer service is overlooked (and implicitly treated as non-existent) in official statistics.

A series of surveys conducted by Brynjolfsson and Hitt (1997) provides evidence that the production of intangible outputs is an important consideration for IT investments. In multiple surveys of IS managers, conducted in 1993, 1995 and 1996, they 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 IS investments (Figure 3). Moreover, firms that place greater emphasis on these intangible outputs have higher productivity than their competitors. Brooke (1992) also found that IT was associated with increases in product variety using publicly available measures including trademark filings. These studies suggest that the failure to account for changes in output quality, product variety, customer service and convenience create substantial biases in measuring the effects of computers.

Brynjolfsson and Hitt (1996, 1998) argue that firm-level studies, unlike industry-level or economy-level studies, may be able to capture some intangible value that is created by IT, even when such value cannot be directly measured. To illustrate, suppose a firm invests in IT to improve product quality and these benefits are recognized and valued by consumers. If other firms do not make similar investments, any difference in quality will lead to differences in the equilibrium product prices that can be charged by each firm. When firms with high quality product 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 IT investment and the difference in revenue will be averaged out. Unless statisticians explicitly account for the change in product quality, little net correlation between IT and (measured) output will be detected. However, when the analysis is conducted across firms, variation in quality will contribute to differences in output and productivity and, thus, will be measured as increases in output elasticity. Thus, to the extent that differences in prices reflect differences in consumer valuations for products (e.g. due to quality, convenience, customer service, customization etc.) firm-level data will better measure these contributions at least in the short run. However, if different prices are due to differences in market power that are not related to consumer preferences, then firm-level data will give a misleading estimate of the productivity effects of IT. In addition, to the extent that spillovers lead the overall quality improvements to become widely adopted by the industry, failure to capture this quality change in the industry deflator will probably systematically understate the contribution of IT investment for the industry.

Zvi Griliches (1994) argued that government data shows many inexplicable changes in productivity, especially in the sectors when output it poorly measured. This point can be illustrated by selected industry-level productivity growth data over different time periods:

Industry	**1948-1967**	**1967-1977**	**1977-1996**
Depository Institutions (~Banks)	.03%	.21%	-1.19%
Health Services	.99%	.04%	-1.81%
Legal Services	.23%	-2.01%	-2.13%

Table: Annual productivity growth for selected industries over different time periods (partial reproduction from Gordon, 1998, Table 3)

According to these figures, a bank today is only about 80% as productive as a bank in 1977; a health care facility is only 70% as productive and a lawyer is only 65% as productive as they were 1977. This suggests the following thought experiment: would you prefer to have a 1977 bank, hospital or lawyer? In 1977, all banking was conducted at the teller window at branch locations during regular "bankers' hours". In 1996, only 55% of banking transactions occur face-to-face and customers now have access to a network of 139,000 ATMs[12] (Osterberg and Sterk, 1997) which provide 24-hour service, 7 days a week in a wide range of locations. Computer-controlled medical equipment has enabled more successful and much less invasive medical treatment; many procedures that previously required extensive hospital stays can now be performed on an outpatient basis; medical tests which involved surgical procedures can now be done using non-invasive imaging devices such as x-rays, MRI, or CT scanners; some surgical procedures can be avoided altogether by improvements in medication and outpatient therapies. A lawyer today has access to a much wider range of information through on-line databases (e.g., Lexis/Nexis) and an increased ability to manage large numbers of legal documents through image processing and document retrieval systems. In addition, some basic legal services, such as the design of a simple will, can now be performed by consumers using standard software packages.[13] All of these examples suggest that there may be substantial value, at least part of which is attributable to computers, which has gone uncounted in industry-level and economy-level productivity statistics. Interestingly, Siegel (1997) found that the measured effect of computers on productivity was substantially increased when he used econometric techniques designed to address various types of measurement error in industry-level data.

[12] This is in addition to approximately 85,000 bank branches in 1996, including banks, thrift offices and bank offices in supermarkets.
[13] For example, Nolo Press has sold over 500,000 copies of WillMaker, a PC-based will writing tool.

One of the most important types of unmeasured benefits arise from new goods. New goods provide a first-order contribution to consumer welfare, yet statistical agencies do not incorporate them into price indices until many years after introduction. For example, the VCR was not incorporated into the consumer price index until 1987, about a decade after they began selling in volume. While this methodology may correctly capture product improvements and price declines for the VCR after 1987, the contribution to consumer welfare and productivity growth before then was missed. This methodological problem may understate the value of computers in two ways. First, the computer industry itself has one of the fastest rates of new product introduction in history. While it may be possible to incorporate improvements in processors or memory into official output statistics, new applications such as personal digital assistants, web browsers and voice recognition systems will go largely unmeasured.[14] Second, new goods like computers enable even more new goods to be developed, produced and managed. For instance, the number of new product introductions in supermarkets has grown from 1,281 in 1964 to 1831 in 1975 and then to 16,790 in 1992 (Nakamura, 1997); the data management requirements for managing this large number of products would have overwhelmed the computer less supermarket of earlier decades. Bar code scanners, inventory systems and computer-based supply chain integration are essential to modern retailing (see Section 2.2).

This collection of results suggests that IT may be associated with increases in the intangible component of output. Because these intangibles are poorly measured, this can lead to systematic underestimates of the contributions of computers. Unfortunately, even firm-level data will not fully capture the value quality improvements or other intangible benefits that are commonplace across an industry (for example, the convenience value of ATMs is not limited to a single bank) because there will be no source of inter-firm variation.

5. Implications for the Macro Economy

While there is increasing evidence that IT, at least over recent time periods, has created substantial value for the firms that have invested in it, it can be a challenge to link these benefits to overall economic performance. One cannot necessarily add up value of IT to each of the firms

[14] For instance, Greenstein (1997) estimates the consumer surplus from extending the capabilities of mainframes and supercomputers exceeds $13Bn per year.

in the economy to get the total value for the whole country. More importantly, the traditional growth accounting 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.

Nonetheless, standard growth accounting techniques provide a useful benchmark for the contribution of IT to economic growth. A good place to start is to note that the nominal value of purchases of IT hardware in the U.S. in 1997 was about 1.4% of GDP. Since the quality-adjusted prices of computers decline by about 25% per year, this means that we could now spend less than 1.1% of GDP and buy the same amount of computers as we did last year. This translates into a direct increase in productivity of over 0.3%. (The fact that Americans collectively choose to spend more on computers each year does not negate this fact. It merely means they have found new uses for these ever-cheaper computers and the actual contribution is somewhat higher.) This value is very close to the 0.3% contribution of computers to consumers surplus estimated by Brynjolfsson (1996) using older data.[15]

One can also look at the contributions of IT to total output growth. Growth accounting calculations by Jorgenson and Stiroh (1995) suggest that computers contributed an average of 0.38% to output growth from 1985 to 1992, while Oliner and Sichel's (1994) estimates range from 0.16% to 0.38% for the 1970-1992 period, depending on which assumptions they use. Oliner and Sichel were unsure that computers would lead to substantial growth:

> *"… the continued rapid growth in the stock of computer hardware and software is not enough, by itself, to significantly boost the contribution of computing services to output growth. Unless the growth rate of business purchases picks up in an extremely dramatic fashion, the only way for computing services to contribute significantly more to output growth in the further than in the past is for the rate of return earned by hardware and software to surge in coming years. Although it is possible that this rate of return will surge in coming years, there are reasons to doubt that such a pickup is yet underway." (Sichel, 1996, p. 132)*

[15] A related approach is to look at the overall effect of IT on the GDP deflator. Reductions in inflation, holding real output constant, is equivalent to productivity growth. Gordon (1998) calculates that "computer hardware is currently contributing to a reduction of U.S. inflation at an annual rate of almost 0.5% per year, and this number would climb toward one percent per year if a broader definition of IT, including telecommunications equipment, were used." Thus, Gordon's estimate implies that computers are adding approximately 0.5% per year of productivity growth.

However, more recent analyses by both sets of authors link the recent surge in measured productivity in the U.S. to increased investments in IT. For instance, Oliner and Sichel (2000) estimate that the contribution of information procession capital to output growth was about 1.1 percent per year for 1996-1999 while Jorgenson and Stiroh (2000), using slightly different assumptions, put the annual contribution at 1.0%. An analysis by Gordon (2000), which also attempts to control for business cycle effects, attributes almost all of the recent increase in trend productivity to improvements in the production of information processing equipment (rather than in productivity improvements in computer-using industries), but finds numbers of a similar order of magnitude.

How do we interpret these numbers? These analyses provide a comprehensive baseline for understanding the productivity contribution of computers and each paper constructs an internally-consistent mapping from measured IT investments to measured output, using data based on the national accounts provided by U.S. government. They show that part of the upturn in measured productivity can be linked to increased real investments in computer hardware and more rapid declines in their quality-adjusted prices. Furthermore, the inclusion of software in the national accounts has added substantially to both output and productivity growth. However, there are also some weaknesses with these approaches, especially if one seeks to know whether computers are pulling their weight.

First, traditional growth accounting presumes that the buyers of computers get what they pay for, since it is based on the quantities purchased and an assumption that the net rate of return does not vary across capital assets. Most economists are comfortable with this assumption. Who better to judge if a computer is worth at least its price than the consumers and businesses who buy them? While some will be disappointed, others will be pleased beyond their expectations. On balance, their seems to be no basis for presuming that buyers have been systematically wrong about their own preferences year after year for what has now been several decades. Nonetheless, it should be stressed that such analyses cannot, by definition, determine whether consumers or firms are getting a "good deal" on their current computer investments.

Second, and more troubling, purchasing decisions are made based on the expected private benefits, not the social benefits. If social returns exceed the private returns, then the above approach will underestimate the contribution of computers. Conversely, if social returns are less than private returns, then the true contribution will be overestimated.

In principal, either situation is possible, but the positive externalities seem more important for computers. Firms often fail to capture the full value created by their investments and innovations, especially when general purpose technologies are involved (Bresnahan and Trajtenberg, 1995). Some of the surplus spills over to other firms in the supply chain or firms that make complementary products. Some of the surplus also spills over to customers, especially in industries where competitors can rapidly imitate innovators. For instance, when banks use IT to lower the costs of transaction processing, this creates opportunities for firms in other industries to productively change some of their business practices. The bank that invests in IT is likely to capture only a tiny fraction of the resulting benefits. Similarly, the annual output contributions of ATMs are poorly approximated by imputing a normal rate or return to their capital stock. The physical capital stock of ATMs is only about $10Billion as compared to over $70Billion for retail bank branches,[16] yet they as much as triple the hours of bank availability and increase the number of banking locations by over 150%. When the benefits occur far from the investment or when the benefits are not included in official GDP measures, traditional growth accounting techniques will be difficult to apply. Historically, only a small fraction of the benefits from most innovations has been captured by the innovator and the same is likely to hold for IT-related business innovations. The explicit effort of firms to benchmark and imitate the best practices of IT-innovators underscores the imperfect ability of the innovators to secure the full value of their investments.[17]

This brings us to the third, and most serious concern with applying the standard growth accounting approach to computers: it ignores the main argument of this paper that IT is only a

[16] This number is based on an average branch capital cost of $1million, as reported in Osterberg and Sterk (1997). The ATM figure is based on $75,000 capital cost per ATM.

[17] Of course, various types of market imperfections may also allow firms to invest in IT to redistribute rents from their customers, suppliers or competitors without improving total welfare (Hitt and Brynjolfsson, 1996). For example, IT can be used to price discriminate among existing customers (charging different prices to different

small fraction of a much larger system of tangible and intangible assets. As discussed in the previous sections, very large investments in human capital, "organizational capital" and "strategic capital", not to mention software, data acquisition, communication equipment, and peripherals, are typically required to make computerization successful for a firm. Thus, it is a mistake to focus entirely on the tangible portion of computer investment and not consider the large changes in complementary factors associated with computers. To the extent that an innovation makes possible other productivity innovations, it will have a large impact on output, even if its factor share is small. To the extent that the costs of developing these other innovations are treated as expenses rather than capital formation, productivity will be underestimated.

For example, the advent of computers gave rise to the software industry. Historically, efforts on software development have been treated as expenses, but recently the government has begun recognizing that software is a capital asset, albeit an intangible one. According to Parket and Grimm (2000), software investment by U.S. businesses and governments grew from barely $10 billion in 1979 to $159 billion in 1998. 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 this an important step in the right direction, there are many other intangible investments that have been associated with the computerization of the economy. What is the magnitude of the complementary investment associated with computerization? If one looks at typical large IT projects, it is clear that computer hardware represents only a small portion of the overall implementation costs. For instance, a survey of enterprise resource planning (ERP) projects found that the average spending on computer hardware accounted for less than 4% of the typical start-up cost of $20.5 million (Gormely et al., 1998). Software licenses and development were also a relatively small share of total costs (16%). The main upfront costs were outside consultants who helped redesign and implement new business processes, internal implementation and deployment staff and employee training. These figures do not include any management time that went into conceiving, evaluating, planning, and managing the overall implementation. Other hidden costs include the time and effort spent reinventing, in large and small ways, many

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customers), thereby capturing rents from consumers, or enable price shopping among vendors, thereby capturing rents from suppliers.

business processes that directly interface with the system, and even many tasks which do not. Most of the start-up costs of implementation are treated as expenses in the year that the system is purchased. However, in terms of their economic effects, the non-recurring costs are more properly thought of as *investments* insofar as they are expected to paying for themselves over several years. Certainly, that is the way managers think of them when they make these spending decisions. While ERP systems are especially intensive in the ratio of "organizational" investment to direct IT investment, most other IT projects also entail non-trivial co-investments. In fact, a survey of three dozen unsuccessful IT projects found that the failure to make adequate complementary investments was one of the most common stumbling blocks (Kemerer and Sosa, 1991).

Analyses by Brynjolfsson and Yang (2000) and Brynjolfsson, Hitt and Yang (2000) provide some estimates on the size of these potential organizational complements which may be useful for assessing their contribution to aggregate productivity growth. Specifically, using 1996 as a base year, the 167 billion dollars of computer capital recorded in the U.S. national accounts were probably only the tip of a much larger iceberg. Based on the 10 to 1 ratio of intangible assets to IT assets found in the Brynjolfsson and Yang study, there may have also been over 1.6 trillion dollars of IT-related complementary assets in the U.S. These intangible assets have not always existed. Instead, they have been created through costly investments by firms over the same years that they made their more visible IT investments.

How might this affect economic growth and productivity? Yang (2000) has made some preliminary estimates. The misclassification of organizational investments as expenses in any given year is partly offset by the "depreciation" of previous years' organizational investments. In a steady state, total output and productivity are little changed even if one correctly classifies the investments. However, the economy has been far from a steady state with respect to computers and their complements. Instead, the US economy has been rapidly adding to its stock of both types of capital. To the extent that this capital accumulation has not been counted as part of output, output has been underestimated. Yang estimates that the true growth rate of US GDP, after accounting for the intangible complements to IT hardware, has been underestimated by an average of over 1% per year since the early 1970s, with the underestimate getting worse over time as net IT investment has grown. The same analysis suggests that multifactor productivity growth has been underestimated by a similar amount. When this intangible capital accumulation slows down, we should be able to convert some of the investment into consumption. This would have the effect of raising GDP growth as conventionally measured by a commensurate amount even if "true" GDP growth were unchanged.

While the exact quantity of intangible assets associated with IT is difficult to assess, the central lesson that emerges from our analysis of the firm-level studies is that these complementary changes are not small. They cannot be ignored in any realistic attempt to estimate the overall contributions of IT.

6. Summary and Conclusion

After two decades of research into IT value, we have substantially improved our understanding of the relationship between information technology and economic performance. The development and use of firm-level data for studying the effects of IT has enabled researchers to identify both the outputs (e.g. intangible benefits for consumers, new intangible assets in firms) as well as the relevant inputs (e.g. complementary organizational investments) of an information and information technology-based economy. Overall, the data suggest that there is no evidence of a "productivity paradox", at least at the firm-level and that computers have had a substantial impact on economic growth for more than 10 years.

In addition, when examining a combination of case evidence and statistical studies, there is a strong indication that organizational complements have a major effect on the contribution of IT. These complementary investments may be as much as an order of magnitude larger than the investments in the technology, suggesting that the real contribution of computers to the economy may be much larger than has been previously believed. The recurring message in the research is that in most cases where IT adds real value, it is only a small part of a much larger system of innovations. Measuring all the components of such systems is never easy, but if researchers and managers at least understand the importance of the intangible costs and benefits of computers, an assessment of their magnitude need not be beyond computation.

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Figure 1: Productivity versus IT Stock (capital plus capitalized labor) for Large Firms (1988-1992) adjusted for industry

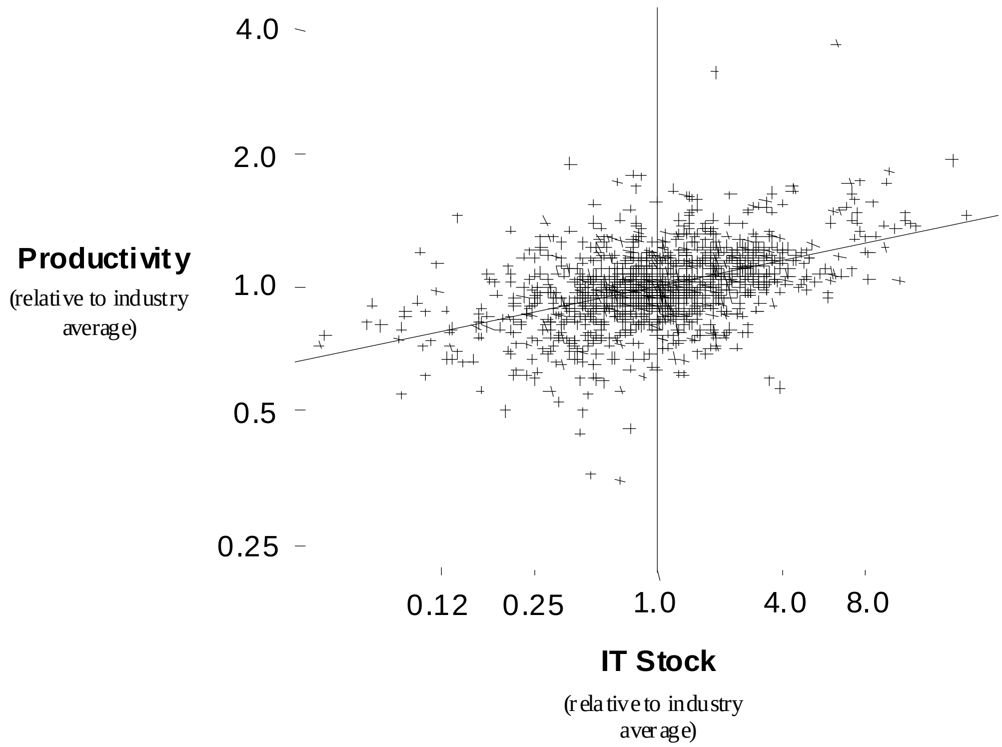

Figure 2: Market Value as a function of IT and Work Organization

This graph was produced by non-parametric local regression models using data from Brynjolfsson, Hitt and Yang (2000). Note: *I* represents computer capital, *org* represents a measure of decentralization and *mv* is market value.

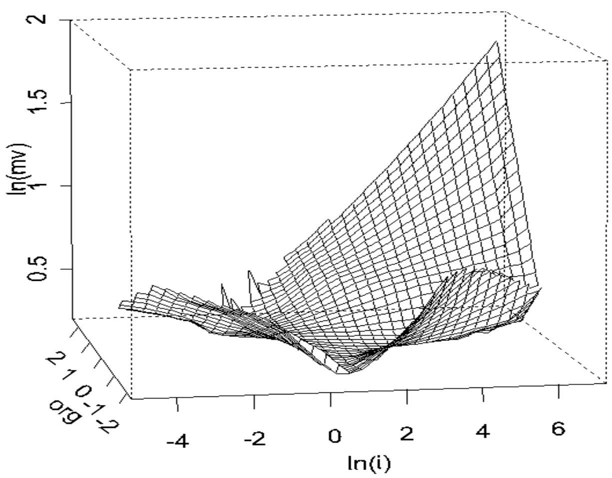

Figure 3: Managers Reasons for Investing in IT (Survey Data: 1995)