Information Technology, Workplace Organization, and the Demand for Skilled Labor: Firm-level Evidence

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ABSTRACT

We investigate the hypothesis that the combination of three related innovations, 1) information technology (IT), 2) complementary workplace reorganization, and 3) new products and services, constitute a significant skill-biased technical change affecting labor demand in the United States. Using detailed firm-level data, we find evidence of complementarities among all three of these innovations in factor demand and productivity regressions. In addition, firms that adopt one or more of these innovations tend to use more skilled labor. The effects of IT on labor demand are greater when IT is combined with the particular organizational investments we identify, highlighting the importance of IT-enabled organizational change.

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I. Introduction

Throughout the 20th century significant shifts in labor demand have favored more skilled and educated workers (Goldin and Katz, 1995; 1998; 1999; Autor, Katz and Krueger, 1998). The shift toward more skilled workers appears to have accelerated in the last 25 years relative to 1940-1973, especially over the period from 1980 until at least the mid-1990s.[1] Over this period, demand has strongly shifted from low- and middle-wage occupations and skills toward highly rewarded jobs and tasks, those requiring exceptional talent, training, autonomy, or management ability. The overall effect has been both large and widespread, substantially shifting relative wages in the top, middle, and bottom of the income distribution.

While many factors have contributed to this increase in inequality, including a slowdown in the growth in the supply of skilled workers (Katz and Murphy, 1992; Autor, Katz and Krueger, 1998; Katz, 1999), an impressive body of empirical studies shows that a significant component of this effect is attributable to skill-biased technical change.[2] Skill-biased technical change (SBTC) means technical progress that shifts demand toward more highly skilled workers relative to the less skilled. It also tends to be something of a residual concept, whose operational meaning is often "labor demand shifts with invisible causes." Not all technological revolutions increase the demand for skilled labor. For instance, the movement from skilled artisans to factory production in the 1800s probably reduced the demand for skilled labor, reflecting a complementarity between the new technologies and unskilled labor (Goldin and Katz, 1998).

However, the size, breadth, and timing of the recent labor demand shift have led many to seek SBTC in the largest and most widespread technical change of the current era, information technology (IT). IT is likely to be particularly important as computing technology increased in power and expanded its scope beyond back-office support to its current pervasive role in large firms. Quantitative research has already made it clear that there is a correlation – if not necessarily causation – between IT use and skill at the worker,[3] firm,[4] and industry[5] level.

In this paper, we make advances on two fronts. First, we look inside the black box of the production function to forge a specific theory of how information technology is used in production. That story sharpens hypotheses about SBTC. In particular, it embeds IT in a cluster of related innovations, notably organizational changes and product innovation, which <u>taken together</u> are the

SBTC. We then examine new firm-level evidence to assess the new hypotheses as well as the most plausible alternative stories of the basic correlation between IT and skill. This not only confirms some of the findings of earlier work, but also enables us to empirically assess the role of firm-level factors like changes in work organization.

We draw on the research literature on how and why firms adopt IT, which has not much focused on the skill demand implications, to build a series of firm-level hypotheses about IT-intensive production. Firms do not simply plug in computers or telecommunications equipment and achieve service quality or efficiency gains. Instead they go through an often lengthy and difficult process of co-invention: IT sellers invent technologies; IT users must co-invent applications to exploit these technologies. Co-invention, like all invention, has both process and product elements.

On the process side, the effective use of IT often involves redesign of a firm's organizational structures. Our hypothesis is that this redesign has labor demand implications. Rapidly decreasing costs and expanding capabilities of computing equipment have created opportunities to automate some types of tasks, to facilitate human workers in other types of tasks, and to generally increase the amount of information available for firms' decision-making. These technological opportunities typically become valuable through adjustment of job responsibilities, decision rights and incentives. The combination of IT and organizational change will be skill-biased if the resulting technology-enabled work structures lead firms to automate mainly low-skill human work, facilitate of mainly high-skill work, or if information-based decision-making overloads more highly skilled managers and professionals so that they become an organizational bottleneck.

On the product side, successful IT use is often combined with product innovation, sometimes through improving the quality, convenience or service associated with existing products, otherwise by introducing entirely new products and services that could not have been economically produced before. Product innovations based on IT include new terms offered by a credit card issuer, new services by a telephone company, a significant increase in stock keeping units (SKUs) by a retailer, or new colors and sizes by a consumer products manufacturer (see Brynjolfsson and Hitt, 2000). A firm's ability to make these product and service innovations depends on its technological capabilities and on its ability to respond rapidly and effectively to

individual customer and marketplace demands, which, in turn, requires new types of organizational structures and a different skill mix for workers.

Accordingly, our definition of the "technical change" that constitutes the current SBTC includes innovation not only 1) in information technology, but also 2) in organizational processes and 3) in the selection of products and services produced and their quality levels. While the innovations in computers are the easiest to measure and best documented, far more resources are probably devoted to the other two types of innovations in most firms (Bresnahan and Greenstein, 1997).

These observations lead us to test hypotheses about a cluster of complementarities that we see as being at the heart of recent changes in labor demand. Intensive use of IT, changes in product and service offerings, and organizational change form a mutually reinforcing cluster of complements for employers. This cluster of complements is, together, a skill-biased technical change calling for a higher-skilled labor mix. Exogenous improvements in IT performance and declining IT prices are the primary catalysts that lead to broader adoption of this set of complementary changes.

II. Framework

Our theoretical framework is summarized in Figure 1, where we display the relevant observable factors in our analysis and the relationships among them. The bottom half of the chart contains the three elements of our hypothesized SBTC: information technology, workplace organization, and the quality of output.

The rapid and continuing decline in the cost of computing and increases in the power and variety of computer systems are an exogenous and powerful change in the environment of the firm. As computers have become faster, smaller, cheaper, more flexible, and easier to network together, the quality-adjusted real price of computers has been declining at a compound rate of about 20% per year through the mid-1990s, and as high as 30% more recently (Gordon, 1992; 2000). This rate, which is rooted in underlying advances in microelectronics, understates the decline in quality-adjusted prices of IT. It omits the substantial improvements in key complements to computers, such as software and networking, which permit more complex and wide-ranging applications of computer power. As a result, demand for IT has been growing very rapidly in real terms. Even in

nominal demand has been growing at about 5% a year. The growth in real demand means that firms must regularly readjust their computer capital stocks.

The progress of IT investment at the firm level is not, however, smooth and direct. A substantial case- and interview-study based literature[6] and a smaller econometric one[7] has examined the causes of variety across firms in the pace and success of IT adoption. It points to complementarities among the use of computers, workplace organization, and output characteristics. The same literature suggests substantial adjustment costs in the latter two complements. This is represented in Figure 1 by the complementarity arrows among the three and by the solid lines around the output and organizational boxes, signifying difficulty of adjustment.

Better measurement and communication associated with IT change the information available within the firm. To the extent that the internal organization of the firm is determined by the economics of information and communication (e.g. Milgrom and Roberts, 1990; Brynjolfsson and Mendelson, 1993; Radner, 1993) these technologies will change the optimal structure of the organization. The case literature reports a variety of such impacts: changes to authority relationships, decentralization of decision authority, shifts in the task content of clerks', operatives', professionals', and managers' work, and changes in reward schemes, among others. This is an important source of complementarity between investments in IT and re-organization of the firm.

Surveys of managers and the case-study literature show that the most important reasons for investing in IT are product quality improvements, notably customer service, timeliness, and convenience (Brynjolfsson and Hitt, 1995, 2000). Flexible machinery and organizational structures can efficiently supply a highly varied output mix (Milgrom and Roberts, 1990; Kelley, 1994). Organizational changes set off by IT investment are intended either to reduce cost or to improve product and service capabilities, although the latter is typically more important (Hammer, 1990; Davenport and Short, 1990; Brynjolfsson and Hitt, 2000). Similarly, the combination of organizational and technological innovation is required to deliver consistently high levels of customer service (Davenport, 1994). All this suggests a three-way cluster of complementarity among product quality improvements, re-organization, and IT investment. Of course, the falling price of IT raises the return not only to investments in IT but also to the other complements, and this has important implications for the nature of its effects.

While inventions of improvements in IT are quickly disseminate throughout the economy, co-inventions of complementary improvements in organization and products are typically local to

the firm (Bresnahan and Greenstein, 1997). Identifying and implementing organizational co-inventions is difficult and costly. They require firms to invest resources and time in innovation and experimentation, and they are uncertain, yielding both successes and failures. The case literature describes many failures of large-scale implementation in computing technology, often attributable to difficulties in implementing concurrent organizational changes (e.g. Kemerer and Sosa, 1991 and Zuboff, 1988). Thus, changes to workplace organization and product characteristics are associated with considerable adjustment costs and experimentation. Many of the adjustment costs are non-monetary, based in the stress on managers and workers who are confronted with the need to change their existing routines and to the reallocation of rents among parties inside and outside the firm. However, they are plausibly as large as or larger than the direct, monetary costs of traditional capital investments in many cases (Jensen, 1993; Brynjolfsson and Yang, 1997; Ito, 1996; Bresnahan, 2000).

In particular, systematic statistical work on investment in computer systems (Ito, 1996) and on migrations to new kinds of computer architectures (Bresnahan and Greenstein, 1997) has shown that the adoption patterns of information technology are associated with substantial adjustment costs. There is also evidence of high stock market valuations of installed IT equipment (Brynjolfsson and Yang, 1997) and on high private returns to IT investment (Brynjolfsson and Hitt, 1996). This suggests quasi-rents to firms that have effectively integrated IT capital into their operations. These rents that arise because non-adopters have not tried, or have tried and failed, to invent complementary workplace or product innovations.

The relationship between investment in IT and investments in the complements has a distinctive dynamic shape. In the long run, declines in the price of IT cause the demand for all the complements to shift out. In any particular short run, however, only a subset of firms will have made successful investments in organizations and product quality. Those firms will have particularly high demand for IT, and will be rapidly adjusting their IT stocks. Others will be waiting for an advance in co-invention or deterred by the costs of adjustment, and will have much lower demand (in the short run, at least) for IT. This view is a summary of previous work on technology and organization. Since the literature has not focused on labor demand effects (despite all of its focus on the reorganization of work) it has not examined the stock or flow of skilled and unskilled labor.

A. Implications for Labor Demand

The primary difference between our approach and previous work on computers and skill-biased technical change is that we look inside the black box of the firm at workplace organization and changing skills. In principle, IT could be a complement or substitute for skilled labor depending on how the technology is used. However, the literature on implementing IT in organizations also suggests two routes by which IT-intensive production might be more skill-intensive, especially if the complementary changes to organizational practices are made (Bresnahan, 1999). We call these *limited substitution* and *information overload.* This leads to the hypothesized (dashed) upward and downward arrows in Figure 1, links of complementarity between skilled labor, and the three-way cluster of complements at the bottom of the figure.

1. Limited Substitution

Computer business systems are most effective in automating routine and well-defined work tasks. That permits substitution out of certain kinds of human effort. Especially in record keeping, remembering, simple calculating, and similar tasks, IT use has led firms to systematically substitute computer decision-making for human decision-making in clerical (and similar routine) work. Advances in artificial intelligence notwithstanding, the scope of this substitution has been limited. Simple decisions, closely related to individual transactions or other operational actions, have been most amenable to computerization. More complex and cognitively demanding work, such as that of managers and professionals, has proved to be remarkably difficult to automate.[8] Computer automation of such work has been correspondingly limited in its scope. Computer automation of clerical and blue-collar work typically does not directly substitute for all of a worker's tasks, but instead for a subset of ancillary tasks. For instance, Murnane, Levy and Autor (1999) find that while computers excel at routine rule-based activities at a large bank they studied, they did not automate the tasks that required exception processing and other tasks for which humans had a comparative advantage. Levy, Beamish, Murnane and Autor (2000) came to similar conclusions in their study of an auto dealership.

Many observers, beginning with Leavitt and Whistler (1958), have argued that the effective use of IT can only come with an associated reorganization of work, and the normative literature on adapting the firm to computerization has included a lively debate about whether the reorganization involves centralization or decentralization of decision authority. More generally, however, some of the substitution may occur only after organizational change has occurred. Since computers have

very different strengths and weaknesses than humans, a re-optimized organization will provide new opportunities to substitute for humans where computers have a comparative advantage.

2. Information Overload

Computerizing routine tasks leads to accumulating data, both intentionally and as a by-product of other goals. A firm can decide to retain a systematic record of all its interactions with a customer, or all of a given employee's interactions with customers, for example. As more and more of the production process is computerized, both record keeping and database analysis become more sophisticated. This offers opportunities for higher-level analytical decision-making. Detailed reports on the success – measured by anything the computer system knows systematically – of individual workers or departments are a kind of management tool that has grown cheaper with the falling costs of computerization. Raw data is fodder for analytic or abstract decision–making, such as analyzing customer needs to target new product development, heightening the value of skilled workers, managers and professionals (unless, as has rarely occurred so far, the computer system itself can make the analytical decisions). For the firm to use this flood of low-cost data and information effectively, it needs to rely on the human intelligence it employs, and this raises the demand for cognitively skilled workers.

Information technology can also be used to bypass the human information processing bottleneck via increasingly automated communication and coordination among workers and groups. Since the information bottleneck will often be most constraining at the tops of hierarchies, computerization may also lead to greater reliance on lateral communications and decentralized decision-making (Brynjolfsson and Mendelson, 1993). These more distant and flexible reporting relationships and incentive schemes change the way both subordinates and superiors relate to their jobs. This induces yet another mechanism by which organizational change and IT together lead to changed skill requirements.

The cluster of product, organizational, and IT change shown in Figure 1 is complex and involves considerable alteration in work and in products – a problem summarized in the literature on IT by saying that effective use of computer systems both enables and necessitates a great deal of invention by the using firms. As computers have grown more central to production, the largest and growing fraction of this inventive activity occurs well outside of the traditional job function of the IT expert or programmer. Standard system development methodologies now call for much greater participation by both managers and line workers in the design of new systems, especially

workers who can integrate technical decisions with operational and strategic business needs (see Lucas, 1996 or McConnell, 1997). This, too, raises the demand for skilled employees.

B. Complementarity of Worker Skill and Organizational Change

In addition, irrespective of the type of worker most affected, computers will generally change the way that human work is measured, controlled, or reported (Baker and Hubbard, 1999). This will involve changes in the firm's information economics, and possibly its organizational structure. Many of these changes to incentive schemes, allocation of decision rights, and so on may imply changes in desired worker skills such as changing the value of workers who can work autonomously (Lazear, 1995, Bresnahan, 1999).

We hypothesize, then, that limited substitution and information overload link IT to labor both directly and indirectly through organizational change. Direct flows include examples like a telephone-switching computer completely replacing a telephone operator in a variety of tasks, an automatic teller machine fully replacing a bank teller, or documents once organized and filed by clerks instead being handled entirely by machine. Indirect flows through organizational change are subtler and may be more pervasive. Work may be restructured to allocate routine, well-defined symbol processing subtasks to computers while separating out subtasks requiring human skills.[9] For instance, consolidated databases may enable workers to access all the data needed to complete an entire process, rather than the task being fragmented across different groups with different private data sources (numerous examples of this issue appear in the case literature on "reengineering" in transactional service environments). To benefit from this technology, firms generally shift workers from a role of functional specialist to process generalist (Hammer, 1990). In manufacturing, the use of flexible machinery and computerized process controls is often coupled with greater worker discretion, which in turn requires data analysis skills and general problem-solving ability (Zuboff, 1988).

Note that all of these arguments apply to the use of IT in the organization, not to the standalone use of personal computers (PCs) by individual workers. Organizational rather than (non-networked) personal computing is the core of the cluster of complements (Bresnahan, 1999).

While we, like much of the literature, focus on cognitive skill measures, IT and organizational change also shift noncognitive skill demands. The monitoring technology associated with computer-based work appears to be systematically related to incentives, at least long-run incentives, which are more closely tied to measurable performance. People vary in their

taste or distaste for those incentives. People also vary in their ability to work autonomously. In parallel, the change calls for changed human interaction talents in supervisors. For instance, supervisors will need more skills in dealing with customers and suppliers, influencing teammates and colleagues, and inspiring and coaching subordinates (Brynjolfsson, Renshaw, and VanAlstyne, 1997). More generally, the changes involve providing the "people skills" that computers lack.

The invention of new products and adaptation to new organizational forms itself requires greater levels of cognitive skill, flexibility and autonomy than in traditional employee roles where the production process is fixed and includes limited discretion. Bartel and Lichtenberg (1987) suggest that cognitive skills may be important in adapting to change generally, notably in the adoption of new technologies. Adaptation to IT-based change may be a standing requirement of the modern firm, resulting in a lasting shift in labor demands.

All these points suggest that the three-way complementarity at the bottom of Figure 1 is further linked to skill. Firms using the cluster of complements will have increased relative demand for high cognitive-skill labor, likely reflected in a more skilled and educated stock of labor and in recruiting and training efforts. The same firms will also be more likely to choose non-hierarchical forms of organizing to bypass the bottleneck. As a result, computerized firms should make greater use of self-managing teams and decentralized decision-making. Furthermore, in these firms, employees with "team" skills and "autonomy" skills should be more valuable.

C. Putting the Hypotheses Together

There are continuous new shocks to quality-adjusted P_{IT}. As a result, the process of co-invention of the cluster of complements at the level of the firm re-occurs over and over. Our economic hypothesis is a complementary relationship at the firm level between labor demand behavior and (i) computerization; (ii) computer-enabled organizational change; and (iii) new computer-enabled forms of output. This cluster of inventions, playing out over years and across many firms, constitutes the technical change that is associated with an increased demand for skilled labor in recent years. While improvements in IT are an important causal force in this story, it is the cluster which is key since IT use is more likely to be effective in organizations with a higher quality of service output mix, decentralized decision-making and more skilled workers.

This theory makes specific predictions for the relationships among IT, organizational characteristics, human capital, and measured output. Firms that invest heavily in IT should also be more likely to adopt a set of organizational changes, typically including more decentralized

decision-making systems and the use of more skilled workers. Furthermore, those firms that successfully combine these elements would be predicted to produce more valuable output than their competitors.

Turning now to measurement, our econometric approach exploits the fact that these complements are associated with different adjustment costs and adjustment speeds. We can therefore examine the relationship between the slower-changing choices (e.g. workplace organization) and the faster-changing ones (training and hiring practices for labor, computer adoption) to measure complementarities. For the complementarities theory, it does not matter whether we think that "computers cause skill" or "skill causes computers": if they are complements, long-run changes in the price of one cutting across all firms will affect the demand for both. Thus the complementarities theory can be investigated by looking either at the impact of computers on skill and organizational change, or the impact of skill and organizational change on computers. One can examine whichever is more appropriate to ensure that it truly is complementarities that are being measured, not some other force. What makes Figure 1 interesting is that the long-run causal change enters the system by way of computers: the element of the cluster of complements that is easiest to alter.

Note also that Figure 1 assigns to each of the three complements at the bottom an observable variable or variables. Our treatment of improvements in the quality of output is based on the point that changes in product characteristics are difficult to measure in a broad cross section of firms. However, those firms that succeed in product innovation will earn quasi-rents, which will appear as increased dollar sales relative to the sales of other firms ($S/S_{\text{other firms}}$) controlling for input consumption. Similarly, workplace organization in general is quite difficult to measure, but we have new survey results at the firm level which we link to our hypotheses. Finally, our measures of the skill mix of labor demand and of computer capital stocks and flows are very conventional.

While earlier studies emphasized a direct causal link between information technology and labor demand, an empirically relevant distinction in our theory is the addition of workplace organization as a central part of the complementarity. The interactions with workplace organization, while critically important, are observable only with detailed firm-level data.

III. Data Description

Our data set matches three sources: (1) a panel detailing IT capital levels and mix over the 1987-1994 period; (2) Compustat measures of other production function inputs and outputs over the 1987-1994 period; and (3) a cross-sectional survey of organizational practices and labor force characteristics. The cross sectional survey was conducted in 1995 and 1996. Once firms with any missing data are removed, we are left with approximately 300 large U.S. firms in our sample. Here we briefly describe each data source and our measures of key variables, with supplementary details in the Appendix.[10]

A. Data Source: Workplace Organization and Labor Force Characteristics

We surveyed senior human resources managers in three waves in 1995-1996. Our 14 questions were largely drawn from prior surveys on workplace organization and human resources practices (see Huselid (1994); Ichniowski, Shaw and Prennushi (1997); and Osterman (1994)). Short definitions, variable names used in formulas and tables, and descriptive statistics can be found in Table 1. The survey offers a snapshot of work organization and related variables at the end of our analysis period.

The universe of potential respondents was limited to firms that reported both computer capital data from Computer Intelligence InfoCorp (essentially the Fortune 1000) and input and output data on Compustat. This yielded a total population of 778 firms which were contacted by telephone to yield 379 survey responses (a response rate of 48.7%). On average, the firms in our sample were 10% larger in value-added (6% in employment), and somewhat more capital/and IT-intensive than non-respondents. The performance of our sample firms was comparable in terms of stock market returns and return on assets (see Appendix Section C for a sample comparison). Approximately 55% of the observations are from manufacturing, mining, or construction firms and 45% are in services. This slight skew toward manufacturing is reflective of the sampled population rather than a bias in response.[11] The firms in our sample are also broadly representative of firms available in Compustat, although there are some deviations. Our sample has a substantially greater proportion of firms in the finance sector (23% versus 13% in the population), and a correspondingly lower number in “other services” (4% in our sample vs. 16% in the population). Again, this appears to be driven more by systematic industry differences in firm size. Otherwise, our industry composition is broadly consistent with this more general population.

We asked the responding managers questions about the labor force at two levels of aggregation: the firm, and its "most typical" establishment. Many of our questions refer to “production employees,” defined as “non-managerial, non-supervisory personnel directly involved in producing a firm’s product or delivering its service” in that typical establishment; this concept corresponds to Osterman’s (1994) "core employee". About two-thirds of employees were production workers for the average firm in our sample.[12]

At the firm level, we obtained the percentages of the labor force in various broad occupational categories (managers, professionals, clerical, skilled blue-collar and unskilled blue-collar). We also measured the extent of computerization with two questions: the percentage of employees who use general-purpose computers, and the percentage who use electronic mail. We also included some additional questions about the manager's perceived effect of computers on the workplace (Table 9) and the degree of computerization of work (Table 2). For clarity, all references to specific variables are written in italics.

1. Human capital

This survey provides us with a rich set of measures related to the demand for human capital (HK). We proxied the firm’s skill demand in three ways. The first two relate to the production workers in the firms’ typical establishment:

- Education mix. Percentage of the production workers with high school education or less (*%HSED*), some college, and completed college (*%COLL*).
- Worker Skills. The responding manager’s assessment of production worker skills (on an arbitrary scale of 1-5) (*SKILL*).

In addition, we have five occupational measures that collectively capture the distribution of skills across the entire firm, as percentages:

- unskilled blue collar (*%US*), clerical (*%CL*), skilled blue collar (*%SK*), managers (*%MG*) and professionals (*%PF*). We also define the percentage of information workers (*% IW*) as the sum of clerical, managerial and professional worker percentages.

Descriptive statistics in these variables and variable names used in the tables can be found in Table 1. Clearly they measure distinct but related aspects of a firm’s stock of human capital. All of these aspects are likely to be quasi-fixed in the short run at the firm level.

The firm can adjust human capital investment policies far more rapidly than its actual stock of human capital. This leads us to construct a further variable measuring these policies, called *HKINVEST*. We base it on the importance of screening for education in hiring (*SCNED*), the fraction of workers receiving training (*TRAIN*) and the importance of cross training (*XTRAIN*). Here, as elsewhere, we standardize by subtracting means and dividing by standard errors.

Let the definition of STD (x) = $(x - \bar{x}) / s_x$.
HKINVEST = STD (STD (*SCNED*) + STD (*TRAIN*) + STD (*XTRAIN*))

2. Workplace organization

The same survey lets us define a measure of the decentralization of workplace organization at the firm's typical establishment. Our measure takes into account four related measures of the importance of self-managing teams among the production workers. These measure (1) team use (*SMTEAM*); (2) team-building activities (*TEAMBLD*); (3) teamwork as a promotion criterion (*PROMTEAM*); and (4) the use of employee involvement groups or quality circles (*QUALCIR*). Two further measures concern the allocation of decision authority between these workers and managers. *PACE* is higher when workers decide on the pace of work; *METHOD* is higher when they decide on its methods. Altogether, we define our decentralized workplace organization variable as:

WO=STD(STD(*SMTEAM*)+STD(*TEAMBLD*)+STD(*PROMTEAM*)+STD(*QUALCIR*)+STD(*PACE*)+STD(*METHOD*))

We chose this variable for several reasons. Pragmatically, the variables in *WO* capture much of the variation across firms in workplace organization. Our specific definition of *WO* has been found to be a useful summary metric – the only non-noise factor in a principal components analysis – in earlier work by Brynjolfsson and Hitt (1997).[13] Second, it has an obvious economic interpretation in terms of decentralizing decision-making to teams. Finally, *WO* as a concept of workplace organization is relatively narrow and specific. This makes our model and econometrics more precise and interpretable, although *WO* is probably not catching all of the relevant organizational changes.

Since our data on organizational characteristics are based on a snapshot at the end of the sample period, we do not know whether each firm had the same organizational characteristics throughout the sample period. Yet the dynamics of *WO* are reasonably clear. It is likely that many

of the firms were in the process of adopting these practices during the sample period.[14] In a measurement sense, much of the *WO* that we measure reflects changes in *WO* over the sample period. Work organization is hard to change but has nevertheless been changing toward the set of practices we label *WO*.

B. Data Source: Information Technology

Our measures of IT use were derived from the Computer Intelligence Infocorp (CII) installation database. CII conducts a telephone survey to inventory specific pieces of IT equipment by site for firms in the Fortune 1000 (surveying approximately 25,000 sites). For our study, CII aggregated types of computers and sites to get firm-level IT stocks. They calculated the value of the total capital stock of IT hardware (central processors, PCs, and peripherals) as well as measures of the computing capacity of central processors in millions of instructions per second (MIPS) and the number of PCs. The IT data do not include all types of information processing or communication equipment and are likely to miss a portion of computer equipment which is either purchased by individuals or departments without the knowledge of information systems personnel, or owned or operated off-site. The IT data also exclude investments in software and applications. Descriptive statistics can be found in Table 2 and more detailed discussion in the Appendix.

C. Data Source: Other Inputs and Sales

We used Compustat firm data to calculate employment levels and labor expense, sales, capital, and value added in constant 1990 dollars. We also used Compustat to assign firms to an approximately 1.5-digit SIC code industry.[15] Table 3 provides descriptive statistics and Appendix Section B provides more discussion.

Some firms provided only partial data or were missing data from Compustat, reducing the sample size for many of the analyses below. In particular, the educational composition was only available for some firms. Our analyses are primarily based on the common sample that has complete data for our core measures. This includes a total of 1331 firm-years of data;[16] analyses based on long differences or cross sections typically use 250 firms.

D. Product and Service Innovation

The most difficult change to observe in terms of the cluster of technological changes is the change in product and service quality and the invention of new products and services (toward the bottom of Figure 1). A firm's success may be one observable indicator of these changes. Firms

with higher quality output for a given set of inputs will likely have greater sales, reflecting a price premium, greater quantities demanded or both. This will be measured as relative differences among firms in the same industry in multifactor productivity.

IV. Empirical Methods

Using the firm-level data, we can test several implications of our hypothesis that the complementary system of IT, decentralized work organization, and innovations in output is in turn complementary with skilled labor. Our data are a mixture of a panel (the CII and Compustat data) and a cross section of organizational and human capital variables observed at the end of the sample period. We can examine cross-sectional relationships at the end of the sample. We can also examine the relationship between the changes over time in some variables and the state of the firm at the end of the sample.

Our strategy is to look at (1) correlations across firms in the use of the hypothesized complements; (2) short-run conditional input or technology choice equations; and (3) simple production functions. Taken together, these analyses are surprisingly informative not only about complementarities but also about alternative interpretations. We use the following basic notation. Q_{cit} is a measure of firm i's choice of one of the hypothesized complements (either an input or a technology) in year t of input *c*; the different *c*'s are IT capital, work organization, and human capital measures.

The short-run input choice functions are of the form

(1) $$Q_{cit} = f(Q_{c'it}, \text{Controls})$$

On the left, we put the Q_c that are easier to vary. $Q_{c'it}$ are measures of the firm's choices of the other inputs/technologies (and hypothesized complements) *c'*. This is a short-run conditional choice equation because it predicts the more easily varied choices, *c*, as a function of the others, *c'*, which are fixed or quasi-fixed at the firm level.[17] Controls include firm size, industry, and production process proxies. Our interpretation is that *c* is demanded more when the *c'* are particularly high because they are complements, i.e., because Q_c is more productive when used together with $Q_{c'}$.

We also estimate production functions of the form

(2) $\text{Log}(S_{it} - M_{it}) = f(L_{it}, K_{it}, Q_{cit}; \text{controls})$

where S is sales, and M is the materials bill, so that the dependent variable is log(value added). Labor and capital are measured in the logs, as well. Our measures of the three potential complements (Q_{cit}) are entered as levels and interactions with one another. Controls include industry and time. Our interpretation of this production function is that the levels of Q_{cit} reflect the degree to which the firm has adopted information technology and new forms of work organization and the degree to which the firm tends to use more highly skilled labor. The interactions address complementarities among those choices. In the case of *process* technical change, the production function interpretation is direct. In the case of *product* technical change, the interpretation is relative; a firm with a better product will take customers away from competitors and have higher sales in Equation 2. We can only measure differences in technical progress between firms; if all firms advance together it cannot be measured in Equation 2.

A. Alternative Explanations

These techniques could measure firm-level complementarities even when there is a non-productivity explanation of the tendency for firms to use *c* and *c'* together. Careful interpretation of a variety of results helps differentiate between productivity and alternative explanations.

One alternative is that the use of *c* and *c'* is simply a coincidence. Unobserved shocks to the value of each of the "complements," correlated in the cross section of firms, would explain the correlation among the hypothesized "complements" and, in some circumstances, explain the conditional input choice results in Equation 1. If the same shocks are correlated with productivity, they can explain the Equation 2 results as well (cf. Athey and Stern, 1998).

The simplest coincidence story is one of an error in aggregation. Human capital, computers, and decentralization each might simply be more useful in some kinds of industries or in some kinds of firms within industries. These might also, coincidentally, be the more productive ones.

Some firms might have luck or skill -- demand shocks or efficiency advantages (not caused by the complementarities). Such firms might use more of each input and have higher measured productivity. A systematic force that leads such firms to use more of the supposed complements would be an alternative. Systematic forces could be:

- The expansion path of inputs as the scale of output rises. Bigger firms buy more of the "complements."
- Managerial rents and free cash flow might lead successful firms to demand more of these particular inputs. Managers might take pleasure from working with smarter and more capable people, and so on.
- Worker rents Rather than computerization and skills being complements, the causation operates in the reverse direction *and* is unrelated to productivity. For example, skilled workers might get computers for fun.[18]

Another possibility might be a fad: some managers might have decided that all three of the complements are useful, with no particular foundation, while others hold back. This should show up in demand but not productivity. A very different kind of "alternative" posits that we are missing some important complementary inputs, such as applications software. Those omitted inputs raise the value of human capital, decentralized work organization, and IT. The econometric interpretation problem this raises is not an economic interpretation problem for us, since this theory is simply a more elaborate version of our basic story. A related story is about causation: rather than computerization causing an increased demand for skills, instead the more firms with skilled workers find computers more productive and buy more of them. That is simply just another version of our story. Such reverse causation -- associated with productivity -- is also complementarity at the firm level. In the long run, as computers grow cheaper, firms will find it in their interest to have skilled workers. We will seek to address and disentangle these alternatives in our empirical work.

V. Empirical Results

A. Correlations

We find that the complements covary in cross-section / time series data. In Table 4, we report the Spearman rank correlations among a high-level measure of workplace decentralization, *WO*, the log of the firm's total IT capital stock, and selected human capital measures. As with many of our analyses, these correlations are within (broad) industry classes and hold constant both firm size (employment) and the occupational composition of the principal production workers in each firm (*PRBL*, *PRCL*). The last control is for the production process; firms whose production workers are professionals or clerical workers may be very different than those whose production

workers are blue collar. Every one of the correlations is positive, though a few are small economically or statistically. Not all the human capital measures are correlated with one another or with IT or *WO*, but *WO* is highly correlated with all the other variables.

Looking behind those broad measures, we see that a variety of alternative measures of IT are significantly correlated with several measures of employees' human capital (Table 5). The correlation is stronger when the measures of IT are taken from the same organizational survey as the human capital data (first three columns) than when we use the IT measures from the separate CII survey. This probably reflects a better match of the unit of observation.[19] The correlation is visible whether we measure human capital by managers' assessments of skills and education requirements, by the educational composition of the workforce, or by occupational composition. Firms that have fewer high-school-educated workers and/or more college-educated ones tend to have more IT. Firms which employ more managers and especially professionals are more likely to have high levels of IT while those with more blue collar workers tend to have less IT. Once again, we are controlling for industry, size, and process.

The same table also shows how the IT measures are correlated with policies for greater *investments* in human capital, such as training and screening new employees on the basis of their education (Table 5, lower rows). The result is less consistent for our other measure of human capital investment, cross-training (*XTRAIN*), although it is generally positive and significantly related to general-purpose computing (*%GP*). IT can also predict greater investments in human capital (*HKINVEST*) even when we control for current levels of human capital (by including *SKILL* and *EDUC* as partial covariates as shown in the bottom rows of the table).

We also find that decentralized workplace organization is correlated with employee human capital however it is measured (Table 4), and (in results not shown) with firms' attempts to increase human capital via pre-employment screening. Other results not shown here (but reported by Brynjolfsson and Hitt, 1997) reveal positive correlations of various measures of IT with our summary measure of decentralization, *WO*, and with the measures that underlie it.

The correlations among IT, human capital and *WO* are consistent with the view that all three are complements or that the same underlying causes or coincidences drive all three.

B. Firm-level demand for IT

Since the easiest-to-vary of the factors in the cluster of complements is computer capital, we first estimate a series of firm-level short-run demand equations for IT. We see how the

relatively fixed factor of human capital and the relatively fixed technology variable of organization predict the more easily variable IT. Our main interpretation of the coefficients of the relatively fixed variables will be as evidence about complementarities, but we will also consider other hypotheses.

We estimate Equation 1 for (log) IT capital stock in a firm as a function of (log) firm value added, (log) firm employment, production process (proxied by primary production worker occupation), our human capital proxies, *WO*, industry and year. Under our hypotheses, *WO* or human capital or both should predict the firm-level demand for IT.

In Table 6, we present estimates of several variants of this IT demand equation. In a very lean specification, we see that firms with a one standard deviation higher level of (production worker) skill have about a 14.2% higher IT demand (Table 6). When a variable is added to this equation for workforce organization (Table 6) we find that it too is substantial and significant. Moreover, the skill effect and the organizational effect are roughly the same order of magnitude (each is measured as standardized deviations from means). Our interpretation is that both are complements with IT. Adding *WO* reduces, but not to zero, the coefficient on skill; since *WO* and skill are also complements with one another, they covary positively.

Other columns show how we added other measures of human capital. In Table 6 we add two workforce education measures; the omitted category is workers with high school education or less. Firms with a higher proportion of college-educated workers (but not those with only some college) have higher demand for IT. When we also add measures of the occupational structure (Table 6) the education coefficient disappears and the (empirically similar) fraction of professionals in the workforce has a positive coefficient. These results together suggest that human capital is a multidimensional concept and is only imperfectly measured by any single variable; it is not obvious whether we can reliably predict the impact of any specific human capital measure from any other. Moreover, given the collinearity between the fraction of professionals (a firm-wide concept) and the education levels of production workers (an establishment/and worker-specific concept), our results are best interpreted as general human capital at the firm level, not as suggesting specific human capital policies.

In our regressions, we <u>can</u> distinguish human capital measures from *WO*, which has roughly the same positive effect however human capital is measured (columns 2, 4, 5), so it appears that demands for high levels of skill and workplace organization are empirically as well as

conceptually distinct. Several of the alternative interpretations depend on mechanisms in which all investment should be high in the firm because the correlation in the inputs is induced by success. Column 6 of Table 6 has the same specification as Column 4, except that the dependent variable is changed from IT capital to non-IT capital. While workplace organization and human capital are good predictors of IT, they are weak predictors of the demand for other types of physical capital, highlighting the special relationship among IT, *WO* and human capital. We should also note that the inclusion of the sector and production process (production worker composition) variables in Table 6 undercuts the aggregation error story that it is simply variety in circumstances that lead to *WO*, IT, and human capital together. It still may be, but it is the within-industry, within-process variety.

The results in Table 6 indicate that various measures of human capital and work organization shift toward the overall demand curve for IT. Firms with more human capital, more decentralized decision-making, and more professionals tend to use more IT.

C. Human Capital Investment Policies

If new forms of work organization and IT together represent the skill-biased technical change, they should also predict skill demand. Not all versions of such an analysis can be reliably undertaken, however, because of the dynamics of factor demand: a firm's stock of human capital is quasi-fixed. Policies related to the recruitment and training of workers, however, can be quickly varied. The versions of Equation 1 reported in Table 7 predict our index of policies toward human capital investment (*HKINVEST*) in the cross-section of firms. Complementarity suggests that IT and workplace organization should affect the demand for human capital investments such as training and the screening of new workers by education.

A spurious correlation could arise if "lucky" firms, those with particularly high efficiency or demand, invest more in more highly skilled workers and, separately, in computers for reasons other than complementarity. Our specification deals with permanent "luck" because it is implicitly differenced: *HKINVEST* is a measure of the rate of change in human capital, not the level. We deal with transitory luck by using the IT variables with four-year lags or by using lagged values as instruments.[20]

Under a variety of specifications of IT, we find that both work organization and IT per worker predict *HKINVEST*, human capital investment policies (Table 7), after controlling for existing human capital levels (*SKILL*) and sector. Firms with high levels of IT and *WO* use high

HKINVEST strategies, whether or not they already have a great deal of human capital, and the effect is a within-sector one rather than reflecting only differences in production process between sectors. Our findings for IT are quite similar to industry-level findings by Wolff (1996) and especially Autor, Katz and Kreuger (1998) in their Table VII. Using industry-level data, they find that the annual change in the college wage bill share is positively related to present and past levels of computerization. In addition to finding a similar relationship (here with *HKINVEST*, not wage bill share, as the dependent variable) in firm-level data, we also identify an important role for workplace organization. The *WO* effect is systematically large and precisely estimated. Given the dynamics of *WO*, the obvious interpretation is that recent changes in workplace organization leave the firm in a position where it needs to adjust its stock of human capital upward.

Some of the contrasts across the specifications are worth noting. First, comparing Col (1) and Col(2), we see that the existing level of human capital (*SKILL*) predicts *HKINVEST* only if *WO* is omitted. Second, the coefficients change very little when current levels of IT are instrumented with past levels of IT instead of using the lagged values of IT (contrast Col (2) with Col (3)). One might interpret these two results to mean that the human capital and IT investments are not a reaction to a short-run free cash-flow shock, but instead reflect a long-run iteration of the complements moving together. When we change the measure of IT to a question about the computer-intensity of work tasks (*COMP*), the coefficient is significantly higher but also less precisely estimated. One might interpret this to mean that broad measures of IT (like *ITCAP*, *MIPS* or *TOTPC*) include both systems tightly connected to the work of the organization and other systems that affect few jobs.[21] In Col (5) and Col (6) we change the measure of computer intensity to *MIPS* and *TOTPC*, respectively. The *MIPS* results are much like those we obtained using *ITCAP*. However, PCs are a relatively weak predictor of *HKINVEST*. We interpret this to mean that it is organizational, not personal, computing that predicts *HKINVEST* in this time period, just as it was the form of computing most strongly predicted by the human capital and *WO* variables above.

D. Complementarities in the Production Function

Complementarities imply increasing marginal returns to Q_c as its complements $Q_{c'}$ rise. We attempt to measure these effects in a production function context. This strategy will not always work to measure complementarities. If all firms' production functions had the same complementarities among IT, workplace organization, and human capital, and if there were no

adjustment costs or mistakes in implementing these strategies, then the three complements would covary highly in a production function regression. Firms' optimizing behavior would have avoided combinations such as “low-IT, and high-human capital,” thereby removing crucial identifying variation from the production function regressors.

In the present inquiry, that argument is considerably less problematic than usual. Indeed, we have just seen that firms in our sample do demand more of one of the complements when the others are high. Two of the complements are subject to large adjustment costs, as we have seen. Furthermore, exploitation of the complementarities involves invention by the firm and so is characterized by routine experimentation from an *ex ante* perspective and frequent "mistakes" from an *ex post* one.[22] We expect to find enough incompleteness in firms' exploitation of the complementarities to measure them in the production function. This approach provides a valuable counterpart to the demand analysis, which provides the strongest results when all firms are successfully exploiting the complementarities.

The production functions reported in Table 8 include controls for industry and year and three types of productive inputs: labor, IT capital, and non-IT capital. Table 8 shows that both IT and various measures of human capital tend to contribute to output separately; however, they are associated with <u>greater</u> increases in output when the level of the other one is also high, which is consistent with complementarities.[23]

The levels of human capital, IT, and *WO* measure the return to use of those technologies at the center of the sample. All columns continue to show the now-familiar finding in firm-level data that IT is measured as highly productive. Like our predecessors, we interpret this as showing the large adjustment costs to the <u>successful use</u> of IT (Brynjolfsson and Hitt, 1996; Brynjolfsson and Yang, 1997) – adjustment costs likely located in work organization or other co-invention, not in installing the IT itself (Bresnahan and Greenstein, 1997). The story for human capital is more ambiguous, depending on the measure we use; "skill" has an approximately zero coefficient, while the coefficient on the percentage of professionals is positive and larger, although both are insignificant.

The Table (columns 4 and 6) shows the new finding that *WO* is also associated with high measured productivity, although the statistical significance of this finding depends on the sample and the other regressors, but is consistent in magnitude. The interpretation is the same as for IT -- substantial adjustment costs are associated with the new organizational technology, proxied by

WO, and the firms that have overcome these adjustment costs by luck or good judgment have high measured productivity.

The interaction terms between IT and human capital are positive and substantial for skill, college education, and professional employment (not shown). The point estimates are economically large, as the measured output elasticity of IT on any of these three measures is substantially higher in firms with more skilled workers. This goes to the economic hypothesis of complementarity, and in a way that provides evidence against “fad” and other nonproductive explanations of the co-movement of the complements. The coefficients are not measured all that precisely, however. For example, *SKILL**log(*ITCAP*) is only of borderline significance, though the college education interaction effect is somewhat stronger statistically. Given the collinearity among the various complements, our sample is only just large enough to identify this effect; comparisons across different subsamples are remarkably robust in magnitude but vary in significance level.

This limit on the information in the data is clear in the final column of the table. When we consider all possible interactions among IT, human capital and *WO*, the coefficients are all positive, but none are precisely estimated. It may be asking too much of the data to interpret this pattern of interaction coefficients very closely, as we have a number of collinear variables and interaction terms. The number of firms who are in categories like "high on *WO*, low on IT, high on human capital" is necessarily relatively small, given what we know from the evidence of complementarities in the demand equations.

The interaction specifications permit us to undertake some simple predicted-productivity calculations that are illuminating. Consider a firm that might be two standard deviations away from the means for industry and year on any or all of the human capital, *WO*, and IT axes. The predicted values from Table 8 indicate that a firm that is high on all three axes has very high predicted productivity -- approximately 7% above a firm that is at the mean on all three, excluding the direct effect of higher IT capital. Interestingly, this is on the same order as the productivity changes associated with various workplace innovations found by Black and Lynch (1997) using a sample of 627 plants during a comparable time period (1987-1993). Their regression coefficients suggest that the cumulative effect of introducing a set of changes including computerization, workplace meetings, self-managing teams, and profit-sharing incentives would be a labor productivity increase of 11 percentage points. However, while they discussed the potential for

complementarities among technology and organization, they did not report any interaction terms between computers and the various work practices.

If we change to the "mixed" cases (high-low-high, etc.) we find that the predicted productivity falls to worse than the mean in almost all cases. The very interesting case of low-low-low is exceptional; it has about the same predicted productivity as the mean, a good bit higher than that for many of the "mixed" cases. This is consistent with the complementarities notion. There is a perfectly workable group of low-low-low, old-style firms. They have internal consistency in their mix of complements, what Milgrom and Roberts (1990) call a "coherent combination" of practices. Importantly, this result argues against heterogeneity arguments as an explanation for the results. While some unobserved firm-level shock, such as free cash flow, could yield positive effects on human capital, IT, and productivity all at the same time, it is difficult to explain why firms with low IT, low human capital and low *WO* have higher productivity than those with one but not the others.[24]

E. Managers' Beliefs

When it comes to assessing causality, social scientists have one advantage over natural scientists: we can ask our subjects why they do what they do. The subjects may or may not fully understand the causality themselves, but at a minimum, they can provide insight into their motivations. Our survey asks managers' opinions on the effects of information technology on work. The managers rate the importance of each of several different effects on a scale of 1-5.

Their responses let us ask two kinds of questions. What do managers think are the important effects on average? This uses managerial opinion the way we often use anecdotes, case studies, and interviews.[25] Managers whose budgets and careers depend in part on making the right decisions about technology and organization have a strong stake in trying to understand the nature of IT-enabled changes. We should discount any theory that contradicts managers' stated assessment of the effects of IT on skills, just as we would discount a theory that contradicts other facts. Second, if managerial opinion is heterogeneous, which views are associated with investment in IT, human capital or WO? As stressed by Athey and Stern (1998), if we understand the factors that drive investment, we can more easily disentangle complementarities from rival explanations for the kinds of correlations we report. Since we hypothesize that the heterogeneity in firms' levels of IT, human capital and work organization is in part driven by differences in managerial beliefs about what investment levels are optimal, we can examine this hypothesis directly.

The marked central tendency of opinion among the responding managers at our sample firms is that computer use increases the need for skilled workers (Table 9, first row, first column);[26] that computers tend to increase workers' autonomy; and that computers increase management's need and ability to monitor workers. There is no marked tendency to think that computers do or do not routinize work (last column, first row). Most of the people who are actually making the investment decisions in IT, human capital and *WO* do seem to detect a complementarity among them. They do not, as is sometimes theorized, believe that computers are deskilling on average or reduce worker autonomy in their firms.[27]

We examine the correlation of these managerial opinions with firm choice variables in the rest of Table 9. This first column stands out; managers' opinions about IT and skill requirements are strongly associated with the IT-organization-human capital cluster. The sole caveat is that this opinion is not significantly correlated with the IT capital variable, though it is correlated with the email and worker computer use variables. Whether we think of heterogeneity in managerial opinion as causing action or caused by action, this pattern is striking. Managers are clearly thinking in terms of the relationship between technical progress and skill demand when they invest in human capital, organizational decentralization, and IT. Managers generally perceive IT as increasing skill requirements and worker freedom, especially in firms that are skill-intensive, have IT-intensive work, and use decentralized workplace organization. We see three explanations for the fact that managers in firms that adopt the new work practices are more likely to detect a complementarity between IT and skilled work. They may have more experience with the new work system (in which case we might judge their assessments to be more accurate); they may be acting on their beliefs by investing more in clusters of complements than their competitors (in which case we have identified one of the sources of heterogeneity); or some additional hidden factor may be driving both sets of variables (in which case we have only taken a partial step toward sorting out the chain of relationships).

The managerial view that IT increases autonomy is the second strongest correlate of the cluster of complements in Table 9, and its scattered positive correlations tell a similar if weaker story than those in the first column. Perhaps the most surprising thing in this table is the plethora of zeros in the computer capital rows. With the exception of changing skills and, to a far lesser extent, changing autonomy, managers' opinions of computers' effects do not predict computerization of work particularly well.

VI. Conclusion

Earlier work found evidence that computers and skilled labor are relative complements in data at the industry (e.g. Autor, Katz and Krueger, 1998; Berman, Bound and Griliches, 1994) and establishment level (e.g. Doms, Dunne and Troske, 1997; Black and Lynch, 1997). In this paper, we find firm-level evidence that is consistent with the existing literature. In addition, we specify and test a new theory of skill-biased technical change in the contemporary economy using firm-level data. Skilled labor is complementary with a cluster of three distinct changes at the firm level: information technology, new work organization, and new products and services.

We identify a number of testable implications of this theory and examine them in a variety of empirical analyses on firm-level data. Since some of the complements are associated with considerable adjustment costs at the firm level (notably work organization and to a lesser extent human capital) while others are getting much cheaper over time (IT) we expect firm heterogeneity in the adoption of these complements, both individually and as a cluster. With regard to the inputs, this implication is strongly born out. IT, *WO*, and human capital are positively correlated, with or without controls for industry and process heterogeneity. The quasi-fixed choices (work organization and human capital levels) are good predictors of the demand for the more variable ones (IT stocks, IT investment, or human capital investment).

On the output side, new products and services are very hard to measure directly in a firm-level dataset covering much of the economy. We believe the firms that are unusually productive are the ones that have overcome the adjustment costs in product or process innovation, and find that IT, *WO*, and human capital interactions (but not always levels of these variables individually) positively predict firm productivity. These results are consistent with the existing literature on IT and organizational change, with predictions of information-economics-based theories of the firm, and with the perceptions of the effects of IT expressed by managers in our sample.

We also examine several alternative explanations not involving productive complementarities between skill and the cluster. While each particular alternative may explain *some* of our reported results, no single alternative story is consistent with *all* the empirical results. If these relationships were merely a <u>managerial fad</u>, the inputs in the cluster would covary with skill, but would not predict firm performance. <u>Demand shocks</u> might increase investments in all inputs and also lead to increased measured productivity. This seems unlikely to be the explanation, as none of our measured effects are present for other types of investment (non-IT

capital). Evidence of complementarities persists when we control for industry sector and production process, undermining the aggregation error hypothesis. Finally, while personal computers or increasingly skilled workers may be a way for managers or workers to consume rents, the strongest effects we measure are due to organizational change and investments in organizational computing such as mainframes. Neither of these is likely to be a consumption good.

Scenarios in which managers of successful firms simply choose to make simultaneous investments in the factors we identify and not in others is consistent with all the results, but is also perfectly consistent with our original explanation. Making reasonable allowance for some of the limitations of our data and for the difficulty of estimating complementarities from a direct production function, there is strong evidence for the cluster-of-complementarities theory of skill-biased technical change, and substantial evidence against other theories.

Our analysis has implications for understanding skill-biased technical change over the last quarter century. First, we provide new evidence, based on firm-level data, that information technology is a source of increased demand for skilled labor and rising wage inequality. While our tables refer only to the 1987-1994 period, it is clear from the literature on the uses of information technology that many of the same effects have been going on since well before the sample period and are likely to continue past it as well. Second, we identify an important set of mechanisms by which labor demand is influenced through organizational redesign. Organizational changes induced by technical change may have a much larger effect on skills than raw technical change. The kinds of organizational change that are complementary to information technology are widespread throughout the firm, and invention of these organizational changes and associated output market improvements are an innovative activity widespread throughout the economy. As information technology grows cheaper and more powerful, it induces more and more complementary investment in the rest of the cluster of changes -- most importantly, for our present purposes, in skilled labor.

Appendix: Data Details

A. Computer Intelligence Infocorp variables

IT Capital (ITCAP). We take the total purchase value of computer equipment as reported by Computer Intelligence Infocorp. (CII) and deflate it using an extrapolation of Gordon's (1990) deflator for computers (price change -19.3% per year). The total purchase value represents the current market value of mainframes, minicomputers, and peripherals, as well as personal computers during the 1991-1994 portion of our sample period. Prior to 1991, the purchase value only represented the value of mainframes, minicomputers, and peripherals, but excluded personal computers.

Central Processing Power (MIPS). This variable is taken straight from the CII database and represents the total processing power of central processors, measured in millions of instructions per second (PCs are not included in this calculation).

Personal Computers (TOTPC). This is also taken straight from the CII database and represents the total number of personal computers in use at the firm.

B. Compustat-based variables

Sales (SALES) Total Sales as reported on Compustat [Item #12, Sales (Net)] deflated by 2-digit industry level deflators from Gross Output and Related Series by Industry from the BEA for 1988-1992, and estimated for 1993-1994 using the five-year average inflation rate by industry. When an industry deflator is not available, we use the sector-level producer price index for intermediate materials, supplies, and components is used (Council of Economic Advisors, 1996).

Ordinary Capital (NITCAP). This figure was computed from the total book value of capital (equipment, structures, and all other capital) following the method in Hall, 1990. Gross book value of capital stock [Compustat Item #7 - Property, Plant and Equipment (Total - Gross)] was deflated by the GDP implicit price deflator for fixed investment. The deflator was applied at the calculated average age of the capital stock, based on the three-year average of the ratio of total accumulated depreciation [calculated from Compustat item #8 - Property, Plant & Equipment (Total - Net)] to current depreciation [Compustat item #14 - Depreciation and Amortization]. The calculation of average age differs slightly from the method in Hall (1990) who made a further adjustment for current depreciation. The constant dollar value of IT capital (as calculated above) was subtracted from this result. Thus, the sum of ordinary capital and IT capital equals total capital stock.

Labor Expense (LABOR). Labor expense was either taken directly from Compustat (Item #42 - Labor and related expenses) or calculated as a sector average labor cost per employee multiplied by total employees (Compustat Item #29 - Employees) when labor expense was not available, and deflated by the price index for Total Compensation (Council of Economic Advisors, 1995). The average labor expense per employee was taken from BLS data on the hourly cost of workers (including benefits) for 10 sectors of the economy. For firms which had labor expense directly reported on Compustat which did not include benefits (identified by Compustat Item - Labor Expense Footnote), we adjusted the labor figure by multiplying the reported labor expense by the total compensation/wages ratio for each sector as reported by BLS.

Employees (EMPLOY). The number of employees was taken directly from Compustat (Item #29 - Employees). No adjustments were made to this figure.

Materials (MATL). *Only used in computations.* Materials was calculated by subtracting undeflated labor expenses (calculated above) from total expense and deflating by the industry-level output deflator. Total expense was computed as the difference between Operating Income Before Depreciation (Compustat Item #13), and Sales (Net) (Compustat Item #12).

Value-Added (VA). Computed from deflated Sales (as calculated above) less deflated Materials.

Sector Dummy Variables. The industry controls used in most analyses in this paper correspond to an intermediate level between 1-digit and 2-digit SIC codes. Based on the reported primary SIC code on Compustat, we construct the following variables:

Mining /Construction (MI) – SIC 11xx - 20xx
Process Manufacturing (PR) – SIC 26xx, 28xx and 29xx
Other Non-Durable Manufacturing (MN) – SIC 20xx – 23xx and SIC 27xx
High Technology Manufacturing (HI) – SIC 36xx – 38xx and 3571 (computers)
Other Durable Manufacturing (MD) – SIC24xx-25xx, 30xx-35xx (except 3571) and 39xx
Transportation (TP) – SIC40xx-47xx
Utilities (UT) – SIC48xx-49xx
Trade (TR) – SIC50xx-59xx
Finance (FI) – SIC 60xx-69xx
Other Services (SR) – SIC70xx-79xx

C. Survey Characteristics

	Sample	Other Fortune 1000 companies in CII and Compustat data sets
Value Added	$971	$871
Labor Expense	$514	$493
Total Capital Stock	$1,947	$1,339
IT Capital Stock	$28.5	$22.4
Total Employees	13,681	13,066
Pretax Return on Assets (1 Year)	5.51%	6.17%
Total Shareholder Return (1 Year)	17.24%	18.69%
Sales Growth (1 Year)	8.99%	11.15%
Number of Firms	379	399

Note: Dollar figures are in millions.
Sample limited to firms with a complete set of production inputs (capital, labor, value-added, IT).

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Table 1: Organizational Practice and Human Capital Survey Variables

	Range	Variable	N	Mean	Std. Dev.
Variables Measuring Organization					
Team-Based Work Organization					
Use of Self-Managing Teams	1-5	*SMTEAM*	345	2.11	1.13
Use of Employee Involvement Groups	1-5	*QUALCIR*	345	2.85	1.21
Use of Team Building Activities	1-5	*TEAMBLD*	345	2.95	1.17
Promote for Teamwork	1-5	*PROMTEAM*	345	3.59	0.95
Breadth of Jobs	1-5	*BROAD*	345	3.25	0.99
Individual Decision Authority					
Who Decides Pace of Work (3=workers)	1-3	*PACE*	345	1.33	0.37
Who Decides Method of Work (same)	1-3	*METHOD*	345	1.39	0.38
Human Capital Measures (Levels)					
Manager's Assessments 1-5					
Skill Level of Work	1-5	*SKILL*	345	3.60	0.86
Education Level	1-5	*EDUC*	345	2.48	0.66
Education					
Workers w/ High School or Less	0-100%	*%HSED*	263	59.3%	27.8%
Workers with Some College	0-85%	*%SCED*	263	23.3%	17.5%
Workers Completed College	0-100%	*%COLL*	263	17.4%	21.0%
Occupation Mix					
Unskilled Blue Collar (%)	0-95%	*%US*	337	18.4%	21.4%
Skilled Blue Collar (%)	0-85%	*%SK*	337	24.7%	21.1%
Clerical (%)	0-80%	*%CL*	337	19.4%	17.6%
Professionals (%)	0-90%	*%PF*	337	20.7%	16.8%
Managers (%)	0-50%	*%MG*	337	16.8%	8.5%
Human Capital (Investment)					
Pre-Employment Screen for Education	1-5	*SCNED*	345	3.31	0.89
Training (% workers involved)	0-100%	*TRAIN*	345	48.0%	36.1%
Cross-train Workers	1-5	*XTRAIN*	345	3.16	0.98

Source: Authors' Survey.

Table 2: IT Variables

	Variable	N	Mean	Std. Dev.
CII Survey*				
Log(IT Capital)	*LITCAP*	333	3.07	1.66
Total MIPS (Millions of instructions/sec.)	*MIPS*	333	2,624	8,737
Total PCs	*TOTPC*	333	4,560	10,997
Organizational Survey**				
Degree of Computerization of Work 1-5	*COMP*	343	3.28	1.11
% Workers using General Purp. Computers	*%GP*	290	53.0%	33.8%
% Workers using E-mail	*%EMAIL*	290	31.0%	32.2%

Source: *CII, **Authors' Survey.

Table 3: Production function variables

	Variable	N	Mean	Std. Dev.
Compustat Variables 1994 Cross Section*				
log(Sales)	*LSALES*	311	7.72	1.00
log(Value Added)	*LVA*	311	6.79	1.02
log(Labor Expense)	*LLABOR*	311	6.17	1.09
log(Non-IT Capital)	*LNITCAP*	311	7.43	1.44
log(Employment)	*LEMPLOY*	311	2.55	1.09
log(IT Capital)	*LITCAP*	311	2.60	1.49
Production Function Controls Production Worker Composition**				
Blue Collar (fraction of jobs listed)	*PRBL*	345	61.9%	46.2%
Clerical (fraction of jobs listed)	*PRCL*	345	31.4%	43.4%
Professional (fraction of jobs listed)	*PRPF*	345	4.6%	17.5%

Source: *Compustat, **Authors' Survey.

Table 4: Correlations between Measures of IT, HK and Organization

Measure	Computer Capital: *ITCAP*	Work Organization: *WO*	Employee Skill: *SKILL*	% College Educated: *%COLL*	% Professionals: *%PF*
Computer Capital (*ITCAP*)	1				
Work Organization (*WO*)	.18***	1			
Worker Skill (*SKILL*)	.12*	.28***	1		
Percent College (*%COLL*)	.05	.34***	.17***	1	
Percent Professional (*%PF*)	.30***	.21***	.06	.21***	1

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (*EMPLOY*) and production worker composition (*PRBL, PRCL*). N=251-401, due to non-response and some measures limited to second and third wave surveys.
Key: * - p<.1, ** - p<.05, *** - p<.01; test is against the null hypothesis that the correlation is zero.

Table 5: Correlations between IT and Human Capital

Measure (scale in parenthesis)	% Use Gen. Purpose Computing: *%GP*	% Use e-mail: *%EMAIL*	Computer-ization of work: *COMP*	Computer Capital: *ITCAP*	Processing Power: *MIPS*	Number of PCs: *TOTPC*
Skills/Education (N=371)						
Skill Levels (*SKILL*)	.20***	.29***	.36***	.09	.15***	.13**
Education (*EDUC*)	.15**	.26***	.24***	.13	.08	.01
Education Distribution (N=237)						
High School Education (*%HSED*)	-.28***	-.37***	-.32***	-.11*	-.18***	-.15**
College Graduate (*%COLL*)	.27***	.36***	.28***	.07	.14	.05
Workforce Composition (N=303)						
Clerical (*%CL)*	-.02	.04	-.05	-.08	-.01	-.03
Unskilled Blue Collar (*%US*)	-.22***	-.25***	-.17***	-.08	-.13**	-.09
Skilled Blue Collar (*%SK*)	-.05	-.05	.05	.05	.09	.02
Managers (*%MG*)	.16**	.13**	.11*	.17**	.15**	.10
Professionals (*%PF*)	.16**	.27***	.18***	.29***	.39***	.28***
HK Investment Policies(N=370)						
Training (*TRAIN*)	.17***	.14**	.20***	.14**	.15***	.14**
Screen for Education (*SCNED*)	.11*	.15***	.28***	.16***	.18***	.21***
Cross-training of workers (*XTRAIN*)	.18***	.07	.07	.02	.02	.03
HK Investment Policies(N=370) (control for *SKILL* and *EDUC*)						
Training (*TRAIN*)	.14**	.10*	.19***	.15***	.14***	.14***
Screen for Education (*SCNED*)	.07	.08	.15**	.16***	.15***	.19***
Cross-training of workers (*XTRAIN*)	.18***	.07	.03	.01	-.05	.01

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (*EMPLOY*) and production worker composition (*PRBL, PRCL*). N=240-372, due to non-response and some measures limited to second and third wave surveys.

Key: * - p<.1, ** - p<.05, *** - p<.01; test is against the null hypothesis that the correlation is zero.

Table 6: IT demand over 1987-1994 as a function of human capital and workplace organization at the end of the sample period

Dependent Variable	Computer Capital: log(*ITCAP*)	Computer Capital: log(*ITCAP*)	Computer Capital: log(*ITCAP*)	Computer Capital: log(*ITCAP*)	Computer Capital: log(*ITCAP*)	Ordinary Capital: log(*NITCAP*)
Specification / Variable		*WO*	Education	Education+ *WO*	Education+ Prof+*WO*	Education+ *WO*
	Col (1)	**Col (2)**	**Col (3)**	**Col (4)**	**Col (5)**	**Col (6)**
Worker Skill (*SKILL*)	.142** (.0559)	.0915 (.0608)	.109* (.0562)	.0756 (.0611)	.0717 (.0622)	.0464 (.0681)
College Education (*%COLL*)			.138** (.0669)	.0108* (.0600)	.0502 (.0756)	-.0745 (.0711)
Some College (*%SCED*)			-.00751 (.0570)	-.0174 (.0573)	-.0141 (.0593)	.0122 (.0603)
Decentralization (*WO*)		.142** (.0642)		.123* (.0641)	.104* (.0630)	.0116 (.0641)
log(Value-Added) log(VA)	.714*** (.115)	.709*** (.115)	.662*** (.124)	.668*** (.123)	.632*** (.125)	.820*** (.223)
log(Employment) log(*Employ*)	.104 (.128)	.0857 (.130)	.154 (.131)	.128 (.131)	.161 (.135)	.0486 (.214)
Professionals (*%PF*)					.133 (.0976)	
Clerical (*%CLER*)					.0391 (.0734)	
Managers (*%MGR*)					-.0209 (.0723)	
Unskilled Blue Collar (*%USBC*)					-.0101 (.0776)	
Controls: Sector Dummies, Year Dummies, Workforce Composition (*PRCL*, *PRPF*)	Controls	Controls	Controls	Controls	Controls	Controls
R^2	49.3%	50.2%	50.0%	50.6%	51.0%	62.3%
N	1331	1331	1331	1331	1331	1313

Key: * - p<.1, ** - p<.05, *** - p<.01

Huber-white robust (clustered by firm) standard errors utilized to account for repeated observations for same firm. Largest common sample used – results similar in maximal sample for each regression (not shown).

Table 7: Relationship between human capital investment and various measures of information technology, with controls for skill and workplace organization

Dependent Variable	Human Capital Investment	Human Capital Investment	Human Capital Investment	Human Capital Investment	Human Capital Investment	Human Capital Investment
Specification / Variable	OLS	OLS	IV	IV	OLS	OLS
	Col (1)	Col (2)	Col (3)	Col (4)	Col (5)	Col (6)
Computerization log(*ITCAP*/*EMPLOY*)$_{-4}$	.180*** (.0673)	.154*** (.0614)				
Computerization log(*ITCAP*/*EMPLOY*)			.184** (.0735)			
Computerization (COMP)				.994* (.522)		
Computerization log(MIPS/*EMPLOY*) $_{-4}$					.172*** (.0644)	
Computerization log(TOTPC/ *EMPLOY*)$_{-4}$						.0812 (.0650)
Work Organization (*WO*)		.419*** (.0589)	.409*** (.0594)	.314*** (.0982)	.403*** (.0607)	.449*** (.0569)
Skills (*SKILL*)	.237*** (.0629)	.0948 (.0607)	.0930 (.0609)	-.240 (.200)	.0911 (.0618)	.100 (.0626)
Industry Controls	Sector Dummies	Sector Dummies	Sector Dummies	Sector Dummies	Sector Dummies	Sector Dummies
N	250	250	250	250	250	250

Key: * - p<.1, ** - p<.05, *** - p<.01
All variables standardized to mean 0, unit variance.
IV: Computerization (*ITCAP*/*EMPLOY* and COMP) instrumented with 4th lagged log(*ITCAP*/*EMPLOY*); all other variables considered exogenous.

Table 8: Productivity effects of computer-human capital and computer-work organization-human capital interactions from 1987-1994 using human capital and workplace organization metrics at the end of the sample

Dependent Variable	log(VA)	log(VA)	Log(VA)	log(VA)	log(VA)	log(VA)
Specification Variable	Baseline	Baseline+ Skills	Baseline + Skills (maximum sample)	Baseline+ Org (maximum sample)	Baseline+ College	Base + Skill + all interactions
	Col(1)	Col(2)	Col(3)	Col(4)	Col(5)	Col(6)
IT Stock (log(*ITCAP*))	.0347** (.0175)	.0330** (.0166)	.0371*** (.0148)	.0358* (.0147)	.0353* (.0181)	.0250 (.0152)
Capital Stock (log(*NITCAP*))	.138*** (.0298)	.140*** (.0295)	.157*** (.0247)	.154*** (.0246)	.144*** (.0293)	.146*** (.0260)
Labor Input (log(*LABOR*))	.753** (.0422)	.753*** (.0416)	.752*** (.0373)	.748*** (.0374)	.743*** (.0407)	.750*** (.0406)
Worker Skill (*SKILL*)		.00167 (.0210)	.00244 (.0155)			-.00953 (.0236)
College Education (*%COLL*)					-.00795 (.0244)	
Professionals (*%PF*)						
IT x Skill (log(*ITCAP*)xSKILL)		.0262 (.0195)	.0224* (.0155)			.0223 (.0231)
IT x College (log(*ITCAP*)x*%COLL*)					.0550** (.0272)	
IT x Professionals (log(*ITCAP*) x *%PF*)						
Work Organization (*WO*)				.0218* (.0129)		.0192 (.0156)
Work Organization x IT (*WO* x log(*ITCAP*))				.0162* (.00844)		.00884 (.0147)
Work Organization x Skill (*WO* x *SKILL*)						.0125 (.0182)
IT-Organization-Skill (*WO* x *SKILL* x log(*ITCAP*))						.0241 (.0162)
Controls	Sector Dummies, Year Dummies	Sector Dummies, Year Dummies	Sector Dummies, Year Dummies	Sector Dummies, Year Dummies	Sector Dummies, Year Dummies	Sector Dummies, Year Dummies
N	1331	1331	2225	2225	1331	1331
R^2	90.8%	90.9%	92.9%	92.8%	91.2%	91.9%

Key: * - p<.1, **- p<.05, *** - p<.01; Huber-white robust (clustered by firm) standard errors utilized to account for repeated observations for same firm. Largest common sample used except for column 3 and 4 which utilizes the full sample – results similar in maximal sample for the other regressions (not shown).

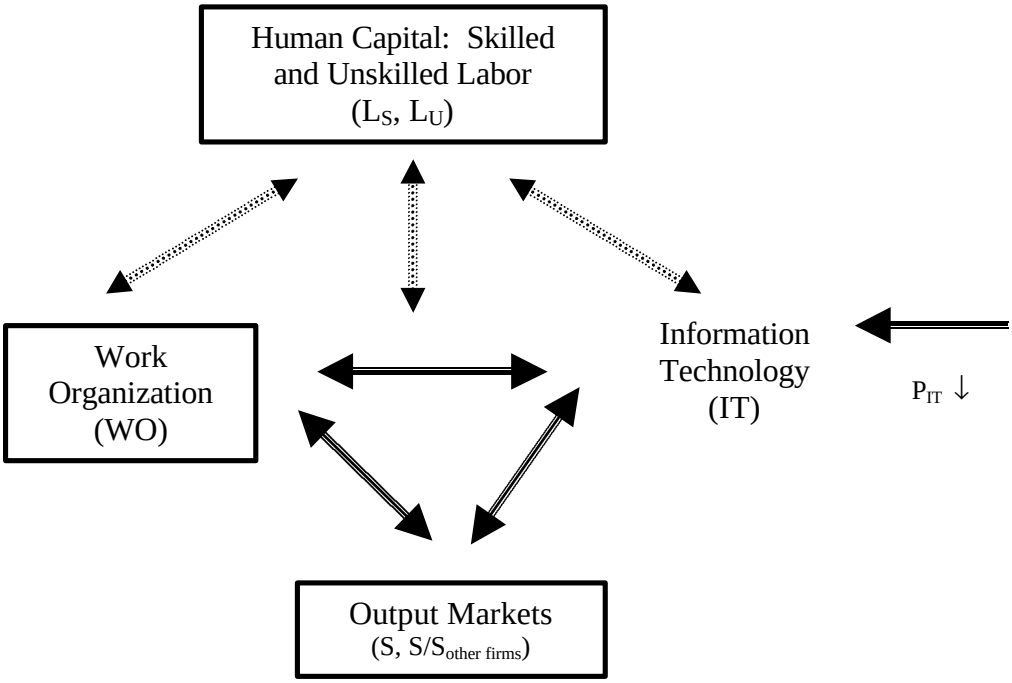
Table 9: Correlations between manager's perception of computer effects with computer use, Human Capital and Decentralization (1-5 scale with 3 = "no change")

Measure	Computers increase Skill	Computers increase Autonomy	Computers increase Monitoring	Computers routinize work
	(*CSKILL*)	(*CFREED*)	(*CMONIT1+ CMONIT2*)/2	(*CROUT*)
Mean	4.17***	3.58***	3.59***	2.96
Computer Capital (*ITCA*P)	.09	-.02	-.06	-.08
% Use Computer (*%GP*)	.25***	.07	-.04	.00
% Use e-mail (*%E-mail*)	.20***	.12**	-.04	-.10*
Work Organization (*WO*)	.19***	.13***	.03	.05
Worker Skill (*SKILL*)	.27***	.20***	.12**	.04
Percent College (*%COLL*)	.19***	.03	-.07	-.12*
Human Capital Investment (*HKINVEST*)	.22***	.10*	-.01	-.01

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (*EMPLOY*) and production worker composition (*PRBL, PRCL*). N=238-295.

Key: * - p<.1, ** - p<. 05, *** - p<.01; test is against the null hypothesis that the correlation is zero (or in the case of variable means, that our survey respondents rated it as "no change")

Figure 1: Innovations in work organization, information technology, and output constitute a complementary system. This new system and its individual components drive increases in the relative demand for skilled labor



Notes

[1] The subsequent trend may have reverted to the 20th century trend in the mid-1990s, although this possibly reflects a greater overall demand for labor due to rapid economic growth rather than a slowing in the demand for skilled labor (Katz, 1999).

[2] There are a number of reviews of the growing empirical literature on wage inequality. See the symposium in the Spring, 1997 issue of the Journal of Economic Perspectives, especially Johnson (1997). Autor, Katz and Krueger (1998) provide a summary of this evidence, a bibliography, and an interesting supply-demand framework. See also Katz and Murphy (1992) and Bound and Johnson (1992) on the supply vs. demand distinction.

[3] See e.g. Krueger, 1993.

[4] Many of these studies treat broader firm-level measures of technological progressivity than merely IT, with a variety of results. These include Doms et al. (1997) and Dunne et al. (1997) for the US, and Aguirrebriria and Alonso-Borrega (1997) for the U.K. For France, Duget and Greenan (1997), Bensaid, Greenan and Mairesse (1997), and Greenan and Mairesse (1999) treat computerization at the firm level.

[5] The IT-intensive industries have seen the demand shift earlier (Wolff, 1996) and to a larger extent (Autor, Katz and Krueger, 1998) than other industries. Chennels and Van Reenan (1998) provide a very interesting discussion of a wide variety of empirical papers looking at all three levels of aggregation. .

[6] See for example Applegate, Cash and Mills (1988), Attewell and Rule (1984), Barras (1990), Crowston and Malone (1988), Davenport and Short (1990), David (1990), Malone and Rockart (1991), Milgrom and Roberts (1990), Murnane, Levy and Autor (1999), Scott Morton (1991), and Zuboff (1988).

[7] See Ito (1996), Bresnahan and Greenstein (1997), and Brynjolfsson and Hitt (1997).

[8] For example, early attempts to implement expert systems in professional or technical environments (including equipment repair, automated computer code generation, and medical diagnoses) have met with failure (Gill, 1995).

[9] This might be thought of as an extreme version of Holmstrom and Milgrom's (1994) principles of job design.

[10] A more detailed description of our data set, and its relationship to earlier studies, can be found in Brynjolfsson and Hitt (1997). The survey instrument can be found at http://grace.wharton.upenn.edu/~lhitt/.

[11] Our sample of Fortune 1000 firms is reduced to 778 firms because many firms (especially service firms) do not report capital stock in a manner consistent with manufacturing firms. Thus we disproportionately eliminate some types of service firms from the sample.

[12] One potential difficulty of our sampling approach is that the practices reported by the respondent may not be representative of the work practices across the entire firm. To address this issue one wave of our survey asked about the uniformity of work practices. For the average responding firm, organizational practices were found to be fairly uniform: 65% said that all production workers have the same work practices and 82% reported that at least 80% of workers had the same work practices.

[13] All the variables in *WO* load positively in the first principal component of all six workplace organization variables in Table 1. Interestingly, Osterman (1994) reports that a similar set of team-oriented practices loaded on the first principal component in his survey of 694 establishments.

[14] The practices we use to define *WO* are very similar to the "new work practices" that, according to Ichniowski et al. (1996), "have become increasingly common among U.S. businesses in recent years." In fact, 49.1% of the establishments in Osterman's (1994) survey (see footnote 23) reported introducing "teams" in the five years prior to his survey year of 1992. He also reports that 38% introduced job rotation practices, 71% TQM programs and 67.9% problem-solving groups in the years between 1987 and 1992; each of these also reflects increased decision-making by line workers.

[15] This divides the economy into 4 manufacturing sectors (continuous process, high-tech, other durable, other non-durable), mining/construction, transport, utilities, finance, trade, and other services.

[16] Results from maximal samples, including as many as 2255 points for some analyse are available from the authors; they are consistent with this smaller sub-sample.

[17] An alternative strategy would be to estimate the long-run system of factor demand equations with both c and c' endogenous. However, we do not observe prices for the factors varying across firms.

[18] DiNardo and Pischke (1997) make this argument -- and provide evidence that it is an important part of the correlation between individual worker wages and PC use observed by Krueger (1993).

[19] The respondents for the organizational practices survey were explicitly asked to consider a representative site for both the HK and IT questions. In contrast, the CII data were for the company as a whole.

[20] Four-year lags were chosen to be sufficiently long to examine long-term effects, but short enough to minimize data loss in our sample.

[21] Or it might simply reflect the fact that both COMP and HKINVEST were drawn from the same survey, improving the match of the unit of observation, while the instrument, lagged IT, comes from the CII data.
[22] See for instance Kemerer and Sosa [1991] for a catalog of disastrous IT projects, many representing substantial investments. Additional references to the difficulty of managing complex IT-enabled organizational change efforts appear in footnotes 6 and 7.
[23] Collinearity occasionally affects the estimates: worker skill and college education are not significant when included in the same regression with (unusually large) IT interaction terms, although they are significant when entered separately (not shown).
[24] One can, of course, construct a more intricate theory to explain the results. For instance, there could be correlated shocks to the productivities of firm-level factors could be confined to certain ranges of use of the factors in different ways in different firms. In empirical science, there is always an alternative explanation of this form; this one is distinctly pre-Copernican in structure.
[25] Discussions with executives at many of the firms in our present sample are an important part of the background to our interpretation of the econometric evidence.
[26] Throughout the survey we use the term "computers." It should be interpreted in the broadest sense of any form of general-purpose computing technology and not limited to specific technologies (such as PCs or mainframes) that we examined separately in earlier analyses using Computer Intelligence data.
[27] These are overall averages. Some managers in our sample did believe that IT led to reduced skill demand or autonomy in their organizations.