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

Timothy F. Bresnahan
Department of Economics, Stanford University
Stanford, CA
Timothy.Bresnahan@stanford.edu

Erik Brynjolfsson
MIT Sloan School of Management
Cambridge, MA
erikb@mit.edu

Lorin M. Hitt
University of Pennsylvania, Wharton School
Philadelphia, PA
lhitt@wharton.upenn.edu

First Draft: January, 1998
This Draft: May, 1999

JEL Categories: L200 Firm Objectives, Organization and Behavior: General; J230 Employment Determination; Demand for Labor; O300 Technological Change: General

We thank Gary Burtless, Paul Romer, Alan Krueger, and participants in the Brookings/MIT Human Capital Conference for valuable comments. This research has been generously supported by the MIT Center for Coordination Science, the MIT Industrial Performance Center and the Stanford Computer Industry Project under grants from the Alfred P. Sloan Foundation and NationsBanc Montgomery Securities. Incon Research, the Center for Survey Research, Computer Intelligence InfoCorp and Informationweek provided or helped to collect essential data.

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

ABSTRACT

Recently, the relative demand for skilled labor has increased dramatically. We investigate one of the causes, skill-biased technical change. Advances in information technology (IT) are among the most powerful forces bearing on the economy. Employers who use IT often make complementary innovations in their organizations and in the services they offer. Our hypothesis is that these co-inventions by IT users change the mix of skills that employers demand. Specifically, we test the hypothesis that it is a cluster of complementary changes involving IT, workplace organization and services that is the key skill-biased technical change.

We examine new firm-level data linking several indicators of IT use, workplace organization, and the demand for skilled labor. In both a short-run factor demand framework and a production function framework, we find evidence for complementarity. IT use is complementary to a new workplace organization which includes broader job responsibilities for line workers, more decentralized decision-making, and more self-managing teams. In turn, both IT and that new organization are complements with worker skill, measured in a variety of ways. Further, the managers in our survey believe that IT increases skill requirements and autonomy among workers in their firms. Taken together, the results highlight the roles of both IT and IT-enabled organizational change as important components of the skill-biased technical change.

Timothy F. Bresnahan
Stanford University
Department of Economics - 6072
Landau Building, Serra Street
Stanford, CA 94305-6072

Erik Brynjolfsson
M.I.T.
Sloan School of Management
50 Memorial Drive, E53-313
Cambridge, MA 02142

Lorin M. Hitt
University of Pennsylvania
Wharton School
1318 Steinberg Hall-Dietrich Hall
Philadelphia, PA 19104

I. Introduction

A. The Growing Demand For Skilled Labor

The distribution of wages and earnings has been spreading out in the United States, leading to increases in income inequality. The wages and earnings of the well-off have been rising much more rapidly than those of low and middle-income workers.[1] An impressive body of empirical studies shows that the proximate cause has been a shift in the demand for labor.[2] Employers' demand has 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 total effect has been both large and widespread, substantially shifting relative wages in the top, middle, and bottom of the income distribution.[3] The shift in labor demand appears to be approximately a quarter of a century old.[4]

Existing studies show that much of the labor demand shift must be explained as skill-biased technical change.[5] Skill-biased technical change (SBΔT) means technical progress that shifts demand toward more highly skilled workers relative to the less skilled.[6] It also tends to be something of a residual concept, whose operational meaning is often "labor demand shifts with invisible causes." The size, breadth, and timing of the labor demand shift have led many to seek SBΔT in the largest and most widespread technical change of the current era, information technology (IT). Existing research has already made it clear that there is a correlation between IT use and skill at the worker[7], firm[8], and industry[9] 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 story of how information technology is used in production. That story sharpens hypotheses about SBΔT. In particular, it embeds IT in a cluster of related innovations, notably organizational changes, which taken together are the SBΔT. 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.

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 more- and less-IT-intensive production. Firms do not simply plug in computers or telecommunications equipment and achieve service quality or efficiency gains. Instead they go through a sometimes lengthy and difficult process of co-invention. IT sellers invent technologies; these do not imply, but only enable, their applications; IT users must co-invent applications. Co-invention, like all invention, has both process and product elements. On the process co-invention side, the effective use of IT often involves changes to organization. There is an IT-based production process for service industries and for the service functions of other industries [Barras, 1990]. Use of this production process involves global changes to firm organization.[10] Examination of the form of the organizational changes suggests testable hypotheses about skill biases in IT-based technical change [Bresnahan, 1997]. The combination of IT and organizational change can be skill-biased if it automates only low-skill human work, or if it creates an information-overload bottleneck for more highly skilled managers and professionals. In either case, the key idea is that the labor demand shift is mediated through organizational changes complementary to IT use.

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, higher service levels (or sometimes efficiencies), 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. If we are right, it is easy to see how the results explain trends in labor demand. The "technical" side of the cluster of complements is the ongoing falls in IT prices and ongoing improvements in IT performance. It is linked to labor demand through its organizational side.

II. There are More Hypotheses Inside the Black Box

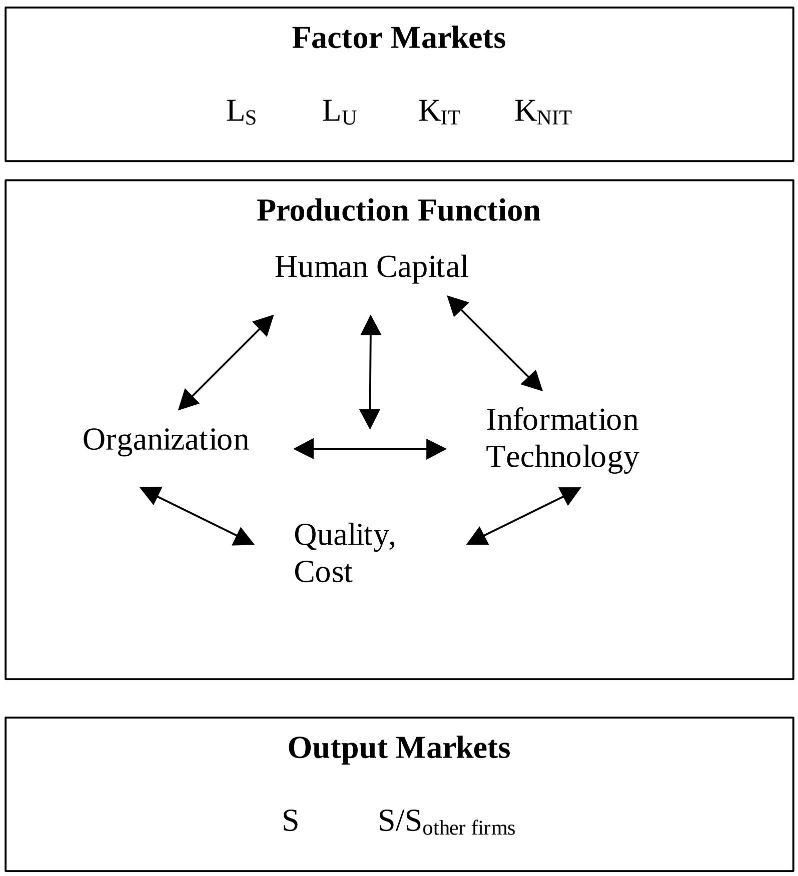
In this section, we briefly review knowledge about IT-using firms' co-invention and the resulting complementarities among IT use, organization, and new products and services. We then explore the implications of this three-way complementarity for labor demand. The background to our analysis is Figure 1, which shows a stylized version of our analytical framework. At the top of the figure are factor markets for skilled and unskilled labor (L_S and L_U) and for IT capital and other capital (K_{IT} and K_{NIT}). In the center is a stylized production process, where solid arrows emphasize the complementarities. At the bottom are output markets.

A. IT, Organizational Innovations and Improved Products and Services are All Complements

An emerging view of the way IT comes to be used in firms is represented by the solid arrows in the production relationship described in Figure 1. This view, which has considerable support in the research literature,[11] emphasizes complementarity among three distinct kinds of technical change.

Figure 1

Production Function, Factor Markets, and Output Markets



The three complements are:

- IT: Technical change embodied in IT Capital
- Quality: New and Improved Products and Services
- Organizational Change

The first complement is invented by technology firms, the other two co-invented by IT-using firms. Taken together, the three complementary forms of technical change are the cluster of technologies we study as a SBΔT. Each of the three complements is associated with distinct dynamic adjustment costs, however, and also with distinct relationships to observables.

1. Technical change embodied in IT Capital

This is the simplest of the three complements in terms of both economic behavior and observables. Information technology advance is embodied in computers and telecommunications equipment. The quality-adjusted price index for the capital goods embodying IT has been falling steadily. Between 1970 and 1990 the real price of IT declined at a compound annual rate of 19.8% and the real quantity consumed by American firms grew even more rapidly. The capabilities of the technology have been expanding steadily. For example, computers have become easier to use, more powerful, and easier to network together. Because IT is embodied, there is an immediate and direct relationship between a firm's choice of information technology and its demand for information technology capital (K_{IT}). To measure this, we can look at both the firm's entire stock of IT capital, and at important classes of that capital such as PCs or servers and hosts. It is far harder to measure the purposes of the business information systems in which the IT capital is embedded. We use a hardware-based view of IT because of this measurement advantage and because it is closely linked to the external technological advance. The level of a firm's use of information technology, and the associated demand for capital, K_{IT}, are not in and of themselves subject to much in the way of invention costs.[12]

2. Organizational change

There are complementarities between IT and the internal organization of the firm. An extensive case- and interview–study based literature (cf footnote 11) emphasizes the difficulties of co-inventing the organizational structures that are optimal when there are high levels of IT capital in production. Better measurement and communication associated with IT change the information available within the firm. To the extent the internal organization of the firm is determined by information economics [Milgrom and Roberts, 1990; Brynjolfsson and Mendelson, 1993] this will change many organizational structures. 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. A central theme is that better measurement and communication permit more objective management and thus more decentralized structure, but there is considerable variety around this central tendency.

The literature underscores the difficulty and uncertainty of all kinds of organizational change. The changes to workplace organization are associated with considerable adjustment costs.[13] There is also a difficult problem of observability associated with organizational change, given its variety and the lack of organizational variables in the accounting and financial records of firms. We deal with the observability problem by moving to a narrow and specific definition of organizational decentralization derived from firms' responses in our survey (details below).

3. New products, services or quality

Sometimes, IT-based production is associated with improvements in efficiency which result in lower costs for the firm. More often, it changes the quality, timeliness, variety or nature of a firm's outputs. Computer-based production leads to higher levels of service or even completely new (service) products. Examples include a manufacturing firm using computerized order-taking and "enterprise resource planning"[14] software to improve the fraction of customer orders it fills on time, or a bank offering nighttime access to checking account balances using database software. These show up in Figure 1 as improvements in costs or quality.

These improvements are notoriously difficult to co-invent, and their appearance may lag behind the other two complements and can be uncertain at the firm level; many elaborate computer-based business information systems fail to produce these benefits. A primary reason for IT implementation failures is that the three-way complementarity between IT, organization, and quality involves very complex changes to the firm.

This complement is associated with weak observability. We cannot directly observe quality improvements at all, and cost improvements must be inferred from productivity. We use competitive success, such as an increase in sales per unit input relative to competitors, as our indicator of relative quality or cost (S or $S/_{S\text{other firms}}$ in Figure 1). This measurement strategy will fail if all firms adopt the same technologies to gain the same improvements. However, since there are adjustment costs associated with the other complements, data variation will be present as firms may well be at different stages.

Viewed as a cluster of technologies which together make up SBΔT, IT, changes in organization, and improvements in product quality have some differences and some aggregate implications. In the aggregate, adjustment costs mean the cluster should diffuse over time. Different elements of the cluster need to be observed in different ways, and different elements provide the force pushing the cluster forward (ever cheaper IT) and holding it back (the adjustment costs of the other two complements).

III. Implications for Labor Demand

As IT has grown cheaper and more powerful, more and more production has switched to IT-intensive processes. The relationship between IT and organizational change leads us quickly to changes in labor demand. We identify two routes by which IT-intensive production might also be more skill-intensive. We call these *limited substitution* and *information overload.* This leads to the hypothesized upward arrows in Figure 1.

A. Limited Substitution

Computer business systems involve the regularization and routinization of certain work tasks. That permits substitution out of certain kinds of human effort. Especially if we look at recordkeeping, remembering, simple calculating and comparing, and similar tasks, the result of IT use and the associated reorganization of work has been the systematic substitution of computer decisionmaking for human decisionmaking 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 remarkably difficult to automate with computers. 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, but instead for a subset of ancillary tasks. Irrespective of the type of worker most affected, computers will generally change the way that human labor is measured, controlled, or reported.

We hypothesize that this limited substitution flows both directly from IT to labor and indirectly through organizational change. Direct flows include examples like a telephone-switching computer replacing a telephone operator in a variety of tasks, an automatic teller machine replacing a bank teller, or documents once organized and filed by clerks instead being handled entirely by machine. Indirect flows through organizational change are more subtle and may be more pervasive. First, some changes like the direct ones may occur only after organizational change has occurred. Since computers have very different strengths and weaknesses than humans, a re-optimized organization will have new opportunities to substitute out of using humans where computers have comparative advantage. Further, in the last section we suggested a series of information economics mechanisms by which IT changed organizations. Many of these changes to incentive schemes, decision allocations, and so on may imply changes in desired worker skills, for example, by changing the value of workers who can work autonomously (Lazear, 1995). More generally, a global and searching organizational change may well involve changes to desired staffing, that is, to the skill mix. Distinguishing between the direct and indirect causal flows is one of our measurement goals. The complementarity between organization and IT means that they often change together and, therefore, the separate casual flows may not be easily distinguished.

B. Information Overload and Increased Demand for Cognitive Skills

Computerizing routine tasks leads to accumulating data, both intentionally and as a by-product of other goals.[15] 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 interactions are so mediated, the sophistication of record keeping and record analysis can grow. This offers opportunities for new uses of human intelligence, deciding what data to use and how to make use of it. It permits changed organizational structures that give more and more data to managers and professionals, correspondingly demanding more analytic or abstract decisionmaking. This flood of data and information puts pressure on the stock of human intelligence in the firm. We hypothesize that the reorganization of work into a more data-based and rule-based form is a complement, not a substitute, for human judgement in decisionmaking. It raises the demand for highly skilled workers.

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. We hypothesize that computerization can lead to attempts to bypass the information overload bottleneck via increasingly automated communication and coordination. Furthermore, 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 decentralized reporting relationships and incentive schemes change the way subordinates relate to their jobs, and superiors as well.

Our hypothesis about IT and organizational change also implies other changes in 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. Not all workers come with equal tolerance for these kinds of incentives. This organizational change requires that subordinates have an increased ability to work autonomously. In parallel, the change calls for changed human interaction talents in supervisors.   For instance, there will be increasing demand for supervisors to be skilled in dealing with customers and suppliers, influencing teammates and colleagues, and inspiring and coaching subordinates. More generally, the changes involve providing the people skills which computers lack.

The three-way complementarity between organization, IT, and product change, affects labor demand through the inventive dynamics of computer-based organizations. Effective use of computer systems involves a great deal of invention by the using firms. It is a complex activity to discover and implement ways to gain from computers' capabilities. As computers have become more powerful, more flexible and more user-friendly, the largest and growing fraction of this inventive activity occurs outside of the programmers' traditional job function.[16] Co-invention is now the duty of those who use computers, directly and indirectly, in large ways and in small ways. This calls for new cognitive skills, having a deep understanding of one's own organization and one's customers' needs.[17] This further raises the demand for high levels of cognitive skills in managers and professionals. Even those managerial and professional workers who never touch computers are having their work transformed in this way, calling for more and more complex bodies of skill and knowledge.

Another direct flow from IT to skilled labor demand has been widely discussed but is likely to be of limited importance. This is the use of personal computers (PCs) by individual workers. By far the largest single use of PCs is for word processing. This is an implausible source of wage dispersion. Similar arguments apply to the other dominant PC applications, spreadsheets and graphics.[18]

We hypothesize changes in the labor demand behavior of more computerized firms, of firms that have both become more computerized and undergone organizational change, and of firms that have changed output along with computerization and organizational change. These firms will seek to address the increased relative demand for high cognitive skill labor by hiring more skilled and educated workers and by investing more heavily in training for existing workers. But firms will also seek non-hierarchical forms of organizing to bypass the bottleneck (e.g. "self-managing teams"). 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 become more valuable. Information technology impacts the optimal organization of work, and impacts the demand for skills both directly and through changes in workplace organization.

C. Putting the Hypotheses Together

We have been writing about labor demand as if it were endogenous while computing, organization, and product quality were exogenous. While helpful for understanding the flow of causation in the long run as technology advances, that unidirectional flow of causation is not a complete discussion of the production technology implied by our story, and especially not a helpful one for measurement. Our series of hypotheses really is about a four-way rather than a three-way complementarity. Under the hypothesized production structure, firms should use high human-capital based production along with IT-based and reorganized workplaces to make higher-quality output. From the perspective of firm decisionmaking, we should expect the first three, which are inputs or managerial choices, to go together. In a measured production function, we should expect them to predict the fourth, output, possibly directly, but more importantly, through their complementarities.

IV. Data Description

Our analysis period is 1987 to 1994. The data set matches three sources: (1) a cross section survey of organizational practices and labor force characteristics conducted in 1995 and 1996, (2) a panel detailing IT capital levels and mix over the 1987-1994 period and (3) Compustat measures of other production function inputs and outputs over the 1987-1994 period. Once 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.[19]

A. Data Source: Workplace Organization and Labor Force Characteristics

We surveyed senior human resources managers in three waves in 1996. Our 14 questions are largely drawn from prior surveys on workplace organization and human resources practices.[20] 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.[21]

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"). Production workers were about two thirds of employment for the average firm responding.[22]

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 that uses general-purpose computers, and the percentage of employees that uses electronic mail. We also included some additional questions about the manager's perceived effect of computers on the workplace (Table 13) and the degree of computerization of work (Table 2).

1. Human capital

This survey provides us with a rich set of measures related to the demand for human capital. We proxy the firm's skill demand at the end of the analysis period 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 or less, some college, and completed college.
- Worker Skills. The responding manager's assessment of production worker skills (on an arbitrary scale of 1-5).

In addition, we have one measure which captures the distribution of skills across the entire firm:

- Occupation mix. Percentage of all the firm's workers in five categories, ranging from unskilled blue collar to managerial. We also define the percent 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 stock of human capital. This leads us to construct a further variable measuring these policies, called HKI. 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 (XTRAI). Here as elsewhere we standardize by subtracting means and dividing by standard errors.

Let the definition of STD (x) = (x- $\bar{x}$) / s_x .

HKI = STD (STD (SCNED) + STD (TRAIN) + STD (XTRAI))

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 (SMTEA), (2) team building activities (TEAMB), (3) teamwork as a promotion criterion (PROTE) and (4) the use of employee involvement groups or quality circles (QUALC). Two further measures concern the allocation of decision authority between these workers and managers. XPACE is higher when workers decide the pace of work, XMETH is higher when they decide its methods. Altogether, we define our decentralized workplace organization variable as:

WO=STD(STD(SMTEA)+STD(TEAMB)+STD(PROTE)+STD(QUAL)+STD(XPACE)+STD(XMETH))

We chose this variable for several reasons. Pragmatically, the variables in WO capture much of the variation across firms in workplace organization.[23] WO has been found to be important in earlier work by Brynjolfsson and Hitt [1997]. Second, it has an obvious economic interpretation in terms of decentralizing to teams. Finally, WO as a concept of workplace organization is narrow and specific, likely catching some but not all of the relevant organizational changes.[24]

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. The reasonable interpretation is that many of the firms have only recently adopted these practices.[25] In a measurement sense, much of WO is ΔWO. WO is hard to change but has recently changed.

B. Data Source: Information Technology

Our measures of IT use were derived from the Computer Intelligence Infocorp (CII) installation database. CII telephone surveys 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 thecomputing 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 purchased by individuals or departments without the knowledge of information systems personnel.[26] The IT data also exclude investments in software and applications. Descriptive statistics can be found in Table 2 and more detailed discussion in Appendix Section VII.A.

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; 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. Approximately 55% of the sample are from the manufacturing, mining, or construction sectors and 45% are in services. 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. We used the largest available sample in each kind of analysis below. Thus there are several different subsamples used in the analysis due to missing data or restrictions to a single year. Most of our analyses use either 2255 or 1834 firm-years of data; analyses based on long differences or cross sections most typically use 250 firms.

D. Strategic Goals

The most difficult observable in terms of the cluster of driver technologies is the change in product and service quality and the invention of new products and services (toward the bottom of Figure 1). Success, which is related to one interpretation of our production function results, may be an observable indicator of these. Firms with higher quality output for a given set of inputs will likely have greater sales. Our interpretation is that firms that enjoy measured productivity growth have achieved one or more of the subgoals listed at the bottom of Figure 1.

V. Empirical Methods

Our hypothesis that IT, human capital, and decentralized organizational structure are all complements has a number of testable implications for the firm-level data. 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-choice equations, and (3) simple production functions. Taken together, these analyses are surprisingly informative not only about complementarities but also about the other interpretations. We use the following basic notation. Q_{cit} is a measure of firm i's choice of one of the hypothesized input complements in year t of input c; the different c's are IT capital, WO, and HK measures.

The short-run input choice functions are of the form

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

We put the more easily varied c on the left. $Q_{c'it}$ are measures of the firm's choices of the other inputs (and hypothesized complements) c'. This is a short-run conditional input choice equation because it predicts the choice of the more easily variable inputs as a function of the others, c', which are fixed or quasi-fixed at the firm level.[27] Controls include firm size, industry, and production process proxies. Our preferred interpretation is that the c factor is demanded more when the c' factors 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 use of distinct product or process technologies used by those particular firms. The interactions address complementarities among those technologies. 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 Theories

Counter-interpretations of our results posit some non-productive reason for the tendency for firms to use c and c' together. These are real alternatives to our interpretation, and we will seek evidence against them. We are, however, going to hold counter-interpretations to the same evidentiary standard as our main story. Instead of considering vague "something might have gone wrong econometrically" alternatives we will examine specific testable possibilities.

It could be 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 -- coincidentally, in the more productive ones.

Some firms might have luck or skill -- demand shocks or efficiency advantages (not caused by these 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" -- this will be straightforward to rebut as the empirical expansion path tends to lead to more of everything, not just more of these particular inputs.
- 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 is in the reverse direction and unrelated to productivity -- skilled workers might get computers for fun, for example.[28]

Finally, there might be a fad: some managers might have decided that all three of the complements are useful, with no particular foundation, while other managers decide to keep their cool. This should show up in demand but not productivity.

There are some things that might at first appear to be criticisms but which are actually disguised agreements with our position. We are missing some important complementary inputs, such as applications software. Those omitted inputs raise the value of HK, WO, and IT. This theory may be true, and that may be a problem for causality in our estimates, but this theory is simply a more elaborate version of our own story, so we are happy to accept it. A related story is about causation: rather than computerization causing an increased demand for skills, a "critic" might argue that firms with skilled workers find computers more valuable and buy more of them. That's just another version of our story. Such reverse causation -- associated with productivity -- is complementarity at the firm level.

VI. Empirical Results

A. Correlations

The complements covary in cross-sectional / time series data.[29] 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 composition of the principal production workers in each firm (PRBL, PRCL). The last control is for the production process; we are concerned that firms whose production workers are professionals or clerical workers may be very different than those whose production workers are blue collar. The correlations are all 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.[30] The correlation is visible whether we measure HK by managers' assessments of skills and education requirements, by the educational composition of the workforce, or by the occupational composition. Firms which 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. These findings are once again 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). IT can predict greater investments in human capital (HKI) even when we control for current levels of human capital (by including SKILL and EDUC as partial covariates in the bottom rows of the table).

We also find that that decentralized workplace organization is correlated with employee human capital (Table 4) and with firms' attempts to increase human capital via training (correlation of .20, p<.01) and employment screening (correlation of .24, p<.01). Finally, as reported by Brynjolfsson and Hitt (1997), there are also positive correlations of various measures of IT with our summary measure of decentralization, WO, and with the measures that underlie it.[32]

The correlations among the various measures of IT, HK 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 most variable 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, production process (proxied by primary production worker occupation), our HK proxies, WO, industry and year. Under our hypotheses, WO or HK or both should be predictive of firm-level demand for IT.

In Table 7, 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 .095 standard deviation increase in IT (Col (7)) or a 13.5% higher demand. When a variable is added to this equation for workforce organization (Col (2)) 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.

Other columns add additional measures of human capital. In Col (3) 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. Our sample size dips somewhat when we include the education measures, as these questions were only asked of some firms in the survey. When we also add measures of the occupational structure (Col (5)) 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 tell the impact of any specific HK measure from any other. Moreover, given that there is strong collinearity between the fraction of professionals (a firm-wide concept) and the education levels of production workers (a establishment and worker specific concept), it suggests that our results are best interpreted as general HK at the firm, not HK necessarily unique to a specific group. Even with these difficulties, we can tell HK from WO, which is measured to have roughly the same effect however the human capital effect is measured (columns 2, 4, 5).

Several of the counter interpretations depend on mechanisms in which all investment should be high in the firm because the correlation in the inputs is induced by success. Col (6), Table 7 has the same specification as Col (4), except that the dependent variable is switched from IT capital to non-IT capital. While WO and HK are good predictors of IT investments, they are weak predictors of the demand for other types of physical capital, highlighting the special relationship among IT, WO and HK. We should also note that the inclusion of the sector and production process (production worker composition) variables in Table 7 also undercuts the aggregation error story that it is simply variety in circumstances that lead to WO, IT, and HK together. It still may be, but it is within-industry, within-process variety.

The results in Table 7 indicate that various measures of human capital and work organization shift outward the overall demand curve for IT. Firms with more human capital, more decentralized decision-making and more professionals tend to use more IT.

1. Dynamic complementarities? Predictors of IT growth

In Table 8 we examine a version of this specification that is, at least in part, more dynamic. To see how the human capital and organizational structure measures predict IT growth, we interact them with a time trend. An observation is still a firm year, and the dependent IT variable is observed for each year of our sample period. The specification is only partially dynamic as human capital and workplace organization are measured at the end of the period. The HK measures and WO get somewhat different dynamical interpretations. As discussed above, the work organization of firms has been changing over the course of the sample period, so WO, measured at the end of the sample period, primarily reflects the extent to which firms have made such changes. In contrast, the human capital and skills stocks of most of our firms have been relatively stable.

In Col (1) of Table 8 we see that the interaction between WO and time predicts increases in IT demand, unlike that between SKILL and time. This effect is a bit fragile. When, in Col (2), we also include education interacted with time, the WO coefficient actually rises but it loses statistical significance. Indeed, no single interaction with time is significant in that column (although the interactions are collectively significant), as the sample is smaller and more collinear variables are interacted with time. There is little evidence of a dynamic effect of HK on IT demand; even when we exclude WOxTIME (Col (3)), the human capital measure does not pick up the effect.

A clearer organizational story emerges when we break up the IT capital stock into components with different organizational roles. In the last two columns of Table 8, the dependent variables are log(MIPS) and log(TOTPC), and the specification is the same as in Col (2). MIPS is a measure of the processing power of the firm's large computers, including both the mainframes that traditionally supported organizational computing and the (mostly minicomputer and workstation) servers which began to replace them in the computer industry "competitive crash." The number of PCs used by the firm, TOTPC, is a measure of individual, not organizational, computing. There are considerable differences between the MIPS (Col (4)) and TOTPC (Col (5)) columns. The coefficients of HK and WO variables in the levels are larger in every case for the MIPS column. The changes over time vary in the same direction.[33] Neither WO nor SKILL has much effect on the change over time in the demand for PCs. In contrast, higher WO firms are investing in more and more MIPS over time -- an effect which is less visible in the results for the firms' total IT stock in Col (2). It is organizational computing and organizational change that are complements.[34] This effect is robust when we include tighter industry controls (2- or 3-digit SIC code) or even separate firm dummies (fixed effects) in results not shown. Both the managerial rents and the worker rents theories of the results are undercut by this variation, as MIPS and WO make very odd on-the-job consumption goods, while PCs make a plausible one.[35]

In light of the adjustment history of the regressors, the most direct interpretation is dynamic exploitation of complementarities. WO is changing in many of our sample firms, and where it is changing, organizational IT is growing. HK is more stable, and so the level of HK at the end of the period does not predict changes in IT. One theory is that WO is a new organizational invention[36] (or IT-enabled WO is a new organizational co-invention). In this theory, those firms that have moved forward in WO have also moved forward in the other complements.[37] A closely related theory is that the complementarity between IT and human capital is long-standing, as is the complementarity between IT and organizations in general, but the complementarity with the particular type of workplace organization that we measure is relatively new and less understood. This would suggest that the IT-HK complementarity is closer to long-run equilibrium while we are observing firms actively investing in both WO and complementary IT.

C. Human Capital Investment Policies

If WO and IT together are the skill-biased technical change, they should 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. We constructed an index of policies toward human capital investment (HKI) and predict it in the cross-section of firms in analyses reported in Table 9. 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.

In these analyses we are concerned that a output demand or efficiency shocks might separately shift demand for both human capital and computers. The spurious correlation could arise if "lucky" firms invest more in more highly skilled workers and computers for any of the reasons described previously. We have attempted to deal with permanent "luck" by using a specification that is implicitly differenced: our variable HKI is much more closely related to ΔHK than to levels of HK. We deal with transitory luck by using the IT variables with four-year lags or by using lagged values as instruments.[38]

Under a variety of specifications of IT, we find that both WO and IT per worker predict HKI, human capital investment policies (Table 9). This finding is after controlling for existing HK levels (SKILL) and sector. Firms with high levels of IT and WO use high HKI strategies, whether or not they already have a great deal of HK, and the effect is a within-sector one rather than reflecting only differences in production process between sectors. The WO effect is systematically large and precisely estimated. The obvious interpretation is that recent changes in workplace organization leave the firm in a position where it needs to adjust its stock of HK upward.

There are some contrasts across the specifications worth noting. If we contrast Col (1) and Col (2), we see that the existing level of human capital (SKILL) predicts HKI only if WO is omitted. The coefficients are little changed 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)). It seems that the HK and IT investments are not a reaction to some short-run free cash-flow shock.[39] 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. This might 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.[40] In Col (5) and Col (6) we change the measure of computer intensity to MIPS and PCs, respectively. The MIPS results are even larger than those using ITCAP. However, PCs are a weak predicator of HKI. The technological story is the same as above. It is organizational, not personal, computing that predicts HKI in this time period, just as it was the form of computing most strongly predicted by the HK and WO variables above.

D. Complementarities in the Production Function

Complementarities imply increasing marginal returns to Q_c as its complements $Q_{c'}$ rise.[42] 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, high-HK, thereby removing crucial identifying variation from the production function regressors.

The present inquiry is one where 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. Yet 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.[43] 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 10 and Table 11 include controls for industry and year and three types of productive inputs: labor, IT capital, and non-IT capital. Table 9 shows that both IT and various measures of human capital tend to contribute to output separately but they are associated with greater increases in output when the level of the other one is also high, which is consistent with complementarities.[44]

In Table 11, we have narrowed the range of alternative treatments of human capital to the skill and information workers variants. The HK variable (and its interactions among the three complements) vary across columns and are identified by the column headers.[45] The columns also vary in terms of the set of interactions included, with one or two interactions included toward the left of the table and all three to the right.

The levels of HK, IT, and WO measure the return to use of those technologies at the center of the sample. All columns continue to show the familiar finding in firm-level data that IT is measured to be highly productive, which we interpret (as do our predecessors) as meaning that there are adjustment costs to the successful use of IT.[46] The story for HK is more ambiguous, depending on the measure we use; "skill" has an approximately zero coefficient, reflecting collinearity with large interaction terms, while that for "information workers" remains positive and significant.

All specifications show the new finding that WO is also associated with high measured productivity. The interpretation is the same as for IT -- there are substantial adjustment costs associated with the new organizational technology, WO, and the firms that have overcome these adjustment costs by luck or good judgement have high measured productivity.

The interaction terms between IT and HK are positive, substantial and significant in all specifications. The measured output elasticity of IT is substantially higher in firms with more skilled workers. This finding is the one most closely related to the important economic issue. It is also evidence against "fad" and other nonproductive theories of the measured complementarity.

The results for the other interaction effects are not as strong. We cannot estimate the three-way interaction (the last two columns) with any precision, nor is it large. The WO and HK interaction always gets a positive coefficient, but the size of the coefficient and the precision with which we estimate it depends on the specification. The same holds for the WO and IT interactions. We note that the WO*HK interaction tends to be large and significant when we measure HK as "skill," while the WO*IT interaction tends to be significant when HK is not measured as "skill." Finally, when we add the three-way interaction, the coefficients on the two-way interactions are reduced, suggesting that the coefficient on any given pair of practices may partially reflect the effects of all three aspects of the complementary system. 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 HK" is necessarily relatively small (especially 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 industry and year mean on any or all of the HK, WO, IT axes. When we look at the predicted values from Table 11 we see that a firm that is high on all three axes has very high predicted productivity -- between 5% and 12% higher (depending on the analysis) above a firm that is at the mean on all three, excluding the direct effect of higher IT capital.[47] 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 one that is exceptional. It has about the same predicted productivity as the mean and a good bit higher than 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. Further, this result argues against heterogeneity arguments as an explanation for the results. While some unobserved firm-level shock (free cash flow is the obvious one) could yield positive effects on human capital, IT and productivity at the same time, it is difficult to explain why firms with low IT, low HK and low WO have higher productivity than those with one but not the others.[48]

An alternative way of examining the same results is to subdivide the sample into “high” or “low” on each of the variables and measure average productivity in each quadrant. Low-low tends to be a relatively high productivity outcome when we treat only two potential complements at a time (Table 12). Those firms in the off-diagonal cells (low-high or high-low) of each table are usually less productive than those which match WO, HK and IT. It should not be surprising that a majority of firms avoid these quadrants. The table shows sample splits for only one measure of HK, namely SKILL. Qualitatively similar results obtain for other measures, such as %COLL, and for related specifications with the output elasticities varying between high and low IT firms. All these results show that we are not simply projecting the positive effect in the positive quadrant into the negative quadrant.[50]

E. Managers' Beliefs

Managerial opinions offer a very different kind of evidence. 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 question. What do managers think are the important effects on average? This uses managerial opinion the way we often use anecdotes, case studies, and interviews.[51] Second, if there is heterogeneity in managerial opinion, which views are associated with investment in HK, WO, or IT?

The responding managers at our sample firms overwhelmingly believed that IT increased the need for skilled workers (Table 13, first row, first column). Similarly, a clear majority reported that they thought that IT tended to increase workers' autonomy. A very similar portion reported that IT increased management’s need and ability to monitor workers. Fewer reported that computers routinize work. On average, the managers neither agreed nor disagreed with this statement (the rest of Table 13, first row).

We examine the correlation of these managerial responses with various measures in the rest of Table 13. This first column stands out, as it is the managers' opinions about IT and skill requirements that are strongly associated with the IT-WO-HK cluster. The sole caveat is that this opinion is not significantly correlated with IT capital, 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 HK, WO, and IT. Managers generally perceive IT as increasing skill requirements and worker freedom, and this is especially true in firms that are skill-intensive, have IT-intensive work and use decentralized workplace organization.

The managerial view that IT increases autonomy is the second strongest correlate of the cluster of complements in Table 13, 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.

VII. Conclusion

In this paper we specify and test a new theory of skill-biased technical change in the contemporary economy. Skilled labor is complementary with a cluster of three distinct changes at the firm level: information technology, organizational change, 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 WO and to a lesser extent HK) 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 HK are positively correlated, with or without controls for industry and process heterogeneity. The quasi-fixed factors (WO and HK) are good predictors of the demand for the more variable factors (IT (stocks or investment), HK investment). On the output side, new products and services are very hard to measure directly in a firm dataset covering much of the economy. We interpret firms that are unusually productive as ones that have overcome the adjustment costs in product or process innovation, and find that IT, WO, and HK 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 simultaneously 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 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.

The implications of this theory for understanding skill-biased technical change over the last quarter century are twofold. 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 activities 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 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, the sector level producer price index for intermediate materials, supplies and components is used [Council of Economic Advisors, 1995].

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

References

Aguirregabiria, Victor; Alonso-Borrego, Cesar (1997). "Employment Occupational Structure, Technological Capital and Reorganization of Production," University of Western Ontario Department of Economics Research Report: 9703.

Applegate, L., Cash, J. and Mills, D. Q. (1988), "Information Technology and Tomorrow's Manager," Harvard Business Review, November-December, pp. 128-136.

Athey, S. and S. Stern, (1998) "An Empirical Framework for Testing Theories about Complementarities in Organizational Design". NBER working paper 6600.

Attewell, P. and J. Rule (1984) "Computing and Organizations: What We Know and What We Don't Know." Communications of the ACM 27(December): 1184-1192.

Autor, D., L. F. Katz and A. B. Krueger. (1998) "Computing Inequality: Have Computers Changed the Labor Market?" Quarterly Journal of Economics. November.

Barras, R. (1990) "Interactive Innovation in Financial and Business Services: The Vanguard of the Service Revolution," Research Policy No. 19.

Bartel, A. and Lichtenberg, (1987) "The Comparative Advantage of Educated Workers in Implementing New Technology", Review of Economics and Statistics, 64 1-11.

Bensaid, A. Greenan, N. Mairesse, J. (1997). "Informatisation, recherche et productivite. (Computerization, Research and Productivity. With English summary.)," *Revue Economique* Vol. 48(3): 591-603.

Berman, E. J. Bound and Z. Griliches (1994) "Changes in the Demand for Skilled Labor within U.S. Manufacturing Industries," Quarterly Journal of Economics, May, 109, 367-98.

Berndt, E. R., C. J. Morrison and L. S. Rosenblum (1992). "High-Tech Capital, Economic Performance and Labor Composition in U.S. Manufacturing Industries: An Exploratory Analysis." MIT Working Paper 3414EFA.

Bound, J. and Johnson, G. (1992) "Changes in the Structure of Wages in the 1980s An Evaluation of Alternative Explanations," American Economic Review 82,3: 371-392.

Bresnahan, T. (1997) "Computerization and Wage Dispersion: An Analytic Reinterpretation." Mimeo. Stanford University.

Bresnahan, T., E. Brynjolfsson, L Hitt "Information Technology and Recent Changes in Work Organization Increase the Demand for Skilled Labor", in M. Blair and T. Kochan, Eds. The New Relationship: Human Capital in the American Corporation, Brookings, revised February, 1999.

Bresnahan, T. and S. Greenstein (1997) "Technical progress and co-invention in computing and in the uses of computers," Brookings Papers on Economic Activity, Micro, pp. 1-83.

Brynjolfsson, E. and L. Hitt (1995). "Information Technology as a Factor of Production: The Role of Differences Among Firms." Economics of Innovation and New Technology. 3 (4): 183-200.

Brynjolfsson, E. and L. Hitt (1996). "Paradox Lost? Firm-level Evidence on the Returns to Information Systems Spending" Management Science (April).

Brynjolfsson, E. and L. M. Hitt (1997). "Information Technology and Organizational Design: Evidence from Firm-level." MIT Sloan School Working Paper.

Brynjolfsson, E. and Mendelson, H. (1993) "Information Systems and the Organization of Modern Enterprise." Journal of Organizational Computing. December.

Brynjolfsson, E. and S. Yang (1997) "The Intangible Costs and Benefits of Computer Investments: Evidence from Financial Markets", Proceedings of the International Conference on Information Systems, December.

Brynjolfsson, E., A. Renshaw and M. V. Alstyne. (1997) "The Matrix of Change," Sloan Management Review, Winter.

Chennells, L. Van Reenen, J. (1998). “Establishment Level Earnings, Technology and the Growth of Inequality: Evidence from Britain,” Economics of Innovation & New Technology, Vol. 5(2-4): 139-64.

Crowston, K. and Malone, T. (1988), “Information Technology and Work Organization,” Chapter 49 in: M. Helander, ed., Handbook of Human-Computer Interactions. Elsevier Science, Amsterdam, pp. 1051-1070.

Davenport, T, and J. Short. (1990) “The New Industrial Engineering: Information Technology and Business Process Redesign.” Sloan Management Review 31.4: 11-27.

David, P. A. (1990). “The Dynamo and the Computer: A Historical Perspective on the Modern Productivity Paradox.” American Economic Review Papers and Proceedings 80(2 (May)): 355-361.

DiNardo, J. and J-S. Pischke. (1997) “The Returns to Computer Use Revisited: Have Pencils Changed the Wage Structure Too?” Quarterly Journal of Economics 1 1 2 (February).

Doms, M. Dunne, T. Troske, K. (1997). “Workers, Wages, and Technology,” The Quarterly Journal of Economics Vol. 112 (1): 253-90.

Duguet, E. Greenan, N. (1997). “La bias technologique: Une analyse econometrique sur donnees individuelles. (Skill Bias: An Econometric Analysis at the Firm Level. With English summary.),” Revue Economique 48 (5): 1061-89.

Dunne, T. Haltiwanger, J. Troske, K.(1997). “Technology and Jobs: Secular Changes and Cyclical Dynamics,” Carnegie-Rochester Conference Series on Public Policy, Vol. 46(June): 107-78.

Gottschalk, P., and T. Smeeding (1997) "Cross-National Comparisons of Earnings and Income Inequality" Journal of Economic Literature, (June), Vol. XXXV, No. 2.

Gottschalk, P. (1997) “Inequality, Income Growth, and Mobility: The Basic Facts,” Journal of Economic Perspectives 11, 2 (Spring): 21-40.

Mairesse, J. and N. Greenan (1999) "Using Employee Level Data in a Firm Level Econometric Study" NBER Working Paper No. W7028, March.

Griliches, Z. (1969). “Capital-Skill Complementarity.” The Review of Economics and Statistics 51(4): 465-468.

Hammer, M. (1990). “Reengineering Work: Don't Automate, Obliterate.” Harvard Business Review (July-August): 104-112.

Huselid, M. (1994). “The Impact of Human Resource Management Practices on Turnover, Productivity, and Corporate Financial Performance.” Academy of Management Journal.

Ichniowski, C. T. Kochan, D. Levine, C. Olson and G. Strauss, (1996) "What works at work: Overview and Assessment", Industrial Relations, Vol. 35, No. 3 (July). P. 299-333.

Ichniowski, C., K. Shaw and G. Prennushi, "The Effects of Human Resource Management Practices on Productivity." American Economic Review, June, 1997.

Ito, H., Essays on Investment Adjustment Costs, Ph.D. Dissertation, Stanford University, September 1996.

Johnson, G. (1997) “Changes in Earnings Inequality: The Role of Demand Shifts,” Journal of Economic Perspectives, 11, 2 (Spring): 41-54.

Juhn, C., K. Murphy and B. Pierce. (1993) “Wage Inequality and the Rise in Returns to Skill,” Journal of Political Economy 101 June: 410-42.

Karoly, L. (1996) "Anatomy of the U.S. Income Distribution: Two Decades of Change," Oxford Review of Economic Policy 12, 1: 76-95.

Katz, L. and K. M. Murphy. (1992) “Changes in Relative Wages, 1963-1987: Supply and Demand Factors,” Quarterly Journal of Economics 107 (February): 35-78.

Kemerer, C. F. and G. L. Sosa, (1991) “Systems Development Risks in Strategic Information Systems.” Information and Software Technology 33(3): 212-223.

Krueger, A.B. (1993) “How Computers Have Changed the Wage Structure? Evidence from Micro Data,” Quarterly Journal of Economics (February): 33-60.

Krugman, P. and R. Lawrence. (1993) "Trade, Jobs, and Wages," NBER WP No. 4478, September.

Lazear, E. (1995). Personnel Economics. Cambridge, MA: MIT Press.

Leavitt, H. J. and T. L. Whisler (1958). "Management in the 1980s." Harvard Business Review (November-December).

Machin, S. (1996) "Changes in the relative demand for skills in the UK labour market." In Booth, A. and Snower, D. (eds.), Acquiring Skills. Cambridge: Cambridge University Press.

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

Milgrom, P. and J. Roberts (1990). "The Economics of Modern Manufacturing: Technology, Strategy, and Organization." American Economic Review 80(3): 511-528.

Milgrom, P. Shannon, C. (1994). "Monotone Comparative Statics," Econometrica Vol. 62(1): 157-80.

Murphy, K. and Welch, F. (1993) "Lessons from Epirical Labor Economis: 1972-1992. Inequality and Relative Wages," American Economic Review, 83, 2.

Osterman, P. (1994). "How Common is Workplace Transformation and Who Adopts It?" Industrial and Labor Relations Review 47(2): 173-188.

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

Steiner, T. D. and Teixeira, D. B. (1991), Technology in Banking: Creating Value and Destroying Profits, Dow Jones Irwin, Homewood, IL.

Wolff, E. N. (1996) "The Growth of Information Workers in the U.S. Economy, 1950-1990: The Role of Technological Change, Computerization, and Structural Change," The C.V. Starr Center for Applied Economics, New York University.

Zuboff, S. (1988) In the Age of the Smart Machine: The Future of Work and Power, New York: Basic Books.

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	SMTEA	345	2.11	1.13
Use of Employee Involvement Groups	1-5	QUALC	345	2.85	1.21
Use of Team Building Activities	1-5	TEAMB	345	2.95	1.17
Promote for Teamwork	1-5	PROTE	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	METH	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	XTRAI	345	3.16	0.98

Source: Authors' Survey. More on data definitions in Section 8.

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. . More on data definitions in Section 8.

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. More on data definitions in Section VIII.

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

Measure	ITCAP	WO	SKILL	%COLL	%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)	%GP	% EMAIL	COMP	ITCAP	MIPS	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***
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***

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 7: IT demand as a function of human capital and organization

Dependent Variable	log(ITCAP)	log(ITCAP)	log(ITCAP)	log(ITCAP)	log(ITCAP)	log(NITCAP)
Specification / Variable		WO	Education	Education + WO	Education + Prof+WO	Education+ WO
	Col (7)	**Col (2)**	**Col (3)**	**Col (4)**	**Col (5)**	**Col (6)**
Worker Skill (SKILL)	.0952*** (.0156)	.0712*** (.0162)	.0837*** (.0224)	.0566** (.0231)	.0539** (.0247)	.0352* (.0202)
College Education (%COLL)			.0977*** (.0240)	.0786*** (.0242)	.0393 (.0276)	-.0506** (.0211)
Some College (%SCED)			-.00672 (.0206)	-.0138 (.0206)	-.0111 (.0217)	.0115 (.0180)
Decentralization (WO)		.0799*** (.0162)		.0935*** (.0220)	.0894*** (.0238)	-.00267 (.0193)
log(Value-Added) log(VA)	.724*** (.0153)	.706*** (.0156)	.657*** (.0205)	.644*** (.0207)	.599*** (.0219)	.656*** (.0181)
Professionals (%PF)					.0957*** (.0291)	
Clerical (%CLER)					.0319 (.0290)	
Managers (%MGR)					-.0155 (.0238)	
Unskilled Blue Collar (%USBC)					-.00511 (.0299)	
Controls: Sector, Year, Workforce Composition (PRCL, PRPF)	Controls	Controls	Controls	Controls	Controls	Controls
R^2	56.4%	56.8%	51.6%	52.3%	50.9%	63.4%
N	2225	2225	1413	1413	1331	1413

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

All regressors have mean zero and standard deviation one.

Table 8: Changes in IT demand

Dependent Variable	log(ITCAP)	log(ITCAP)	log(ITCAP)	log(MIPS)	log(TOTPC)
Specification / Variable	Skill, WO, Interactions	Skill, Education, WO, Interactions	Skill, Education , WO	Skill, Education, WO, Interactions	Skill, Education, WO, Interactions
	Col (1)	Col (2)	Col (3)	Col (4)	Col (5)
Worker Skill x Time (SKILL x YEAR)	.000255 (.00759)	-.0194 (.0220)	-.00557 (.0203)	.0191 (.0212)	.00812 (.0214)
WO x Time (WO x YEAR)	.0183*** (.00766)	.0358 (.0219)		.0810*** (.0218)	-.00147 (.0214)
College Ed. x Time (%COLLxYEAR)		.00656 (.0210)	.0109 (.0207)	-.00339 (.0203)	.0167 (.0204)
Worker Skill (SKILL)	.0438*** (.0191)	.0560*** (.0247)	.0543*** (.0247)	.0414* (.0239)	.0382 (.0241)
College Education (%COLL)		.0388 (.0276)	.0392 (.0277)	.0629** (.0267)	-.0119 (.0269)
Decentralization (WO)	.0668*** (.0186)	.0876*** (.0238)	.0890*** (.0238)	.0945*** (.0231)	.0869*** (.0233)
log(Value-Added) log(VA)	.647*** (.0186)	.600*** (.0219)	.599*** (.0219)	.456*** (.0231)	.561*** (.0214)
Professionals (%PF)	.133*** (.0206)	.0967*** (.0291)	.0958*** (.0291)	.139*** (.0282)	.0667** (.0284)
Controls: Sector, Year, Composition (PRBL, PRPF, %MG, %CL, %SK), %SCED	Controls	Controls	Controls	Controls	Controls
R^2	53.7%	51.0%	50.9%	54.1%	53.3%
N	1854	1331	1331	1331	1331

Key: * - p<.1, ** - p<.05, *** - p<.01: All variables standardized to mean 0, unit variance except interaction terms which represent a standardized variable multiplied by a mean 0 time measure (units are years).

Table 9: Human Capital Investment Policies.

Dependent Variable	HKI	HKI	HKI	HKI	HKI	HKI
Specification / Variable	OLS, IT/E	OLS, IT/E	IV: IT/E	IV: COMP	IV MIPS:	OLS PCs:
	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(TOTPC/employ)					.277*** (.0977)	
Computerization $log(MIPS/employ)_{-4}$						.146 (.0981)
Work Organization (WO)		.419*** (.0589)	.409*** (.0594)	.314*** (.0982)	.403*** (.0607)	.449*** (.0569)
Skills (SKILL)	.237*** (.0629)	.0948 (.0607)	.0930 (.0609)	-.240 (.200)		
Industry Controls	Sector	Sector	Sector	Sector	Sector	Sector
N	250	250	250	250	250	250

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

Table 10: Production Functions with IT-HK and IT-WO interactions

Dependent Variable	log(VA)	log(VA)	log(VA)	log(VA)	log(VA)
Specification / Variable	Baseline	Baseline+ Skills	Baseline+ College	Baseline+ Prof'l.	Baseline+ Info Workers
IT Stock (log(ITCAP))	.0383*** (.00698)	.0372*** (.00702)	.0408*** (.00967)	.0347*** (.00751)	.0333*** (.00746)
Capital Stock (log(NITCAP))	.155*** (.00757)	.157*** (.00755)	.152*** (.00994)	.152*** (.00830)	.148*** (.00796)
Labor Input (log(LABOR))	.754*** (.00939)	.753*** (.00934)	.748*** (.0119)	.754*** (.0103)	.753*** (.00997)
Worker Skill (SKILL)		.00244 (.00664)			
College Education (%COLL)			-.00518 (.0104)		
Professionals (%PF)				.0223*** (.00774)	
Information Workers (%IW)					.0246*** (.00892)
IT x Skill (log(ITCAP)xSKILL)		.0301*** (.00657)			
IT x College (log(ITCAP)x%COLL)			.0637*** (.0103)		
IT x Professionals (log(ITCAP) x %PF)				.00521 (.00659)	
IT x Information Workers (log(ITCAP) x %IW)					.0192*** (.00671)
Controls	Sector Year	Sector Year	Sector Year	Sector Year	Sector Year
N	2225	2225	1413	1854	1854
R^2	92.7%	92.8%	90.9%	91.7%	91.7%

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

Table 11: Production Functions with IT-HK -WO interactions

Dependent Variable	log(VA)	log(VA)	log(VA)	log(VA)	log(VA)	log(VA)
Specification / Variable	HK as Skill	HK as Info Workers	HK as Skill	HK as Info Workers	HK as Skill	HK as Info Workers
IT Stock log(ITCAP)	.0352*** (.00705)	.0302*** (.00748)	.0345*** (.00706)	.0289*** (.00753)	.0335*** (.00723)	.0310*** (.00767)
Human Capital (*varies*)	-.00426 (.00664)	0254*** (.00679)	.000414 (.00712)	.0223*** (.00881)	-.00140 (.00720)	.0254*** (.00911)
Decentralization (WO)	.0231*** (.00702)	.0267*** (.00716)	.0216*** (.00703)	.0265*** (.00761)	.0216*** (.00720)	.0268*** (.00716)
IT x HK (*varies*)	.0245*** (.00722)	.0192*** (.00671)			.0216*** (.00735)	.0253*** (.00731)
WO x HK (*varies*)			.0238*** (.00633)	0114 (.00696)	.0153** (.00674)	.00662 (.00715)
IT x Work Org. log(ITCAP) x WO	.0123* (.00657)	.0317*** (.00691)			.00934 (.00670)	.0319*** (.00695)
HK x WO x log(ITCAP) (*varies*)				.	.00351 (.00646)	.00422 (.00737)
Labor Input log(LABOR)	.749*** (.00939)	.747*** (.00993)	.752*** (.00936)	.750*** (.00995)	.750*** (.00939)	.747*** (.00790)
Capital Stock log(NITCAP)	.156*** (.00754)	.146*** (.00789)	.155*** (.00754)	.148*** (.00794)	.156*** (.00753)	.146*** (.00790)
Controls	Sector Year	Sector Year	Sector*** Year	Sector*** Year	Sector*** Year	Sector*** Year
N	2225	1854	2225	1854	2225	1844
R^2	92.8%	91.8%	92.8%	91.7%	92.8%	91.8%

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

Table 12: Productivity with Matches and Mismatches on Complements

Table 12A: IT x HK (Using ITCAP and SKILL, respectively)

IT \ HK	Low	High
High	-.0293 (.0221) N=552	.0422 (.0199) N=762
Low	0 (N/A) N=561	-.0321 (.0174) N=358

Standard Error in parenthesis

Pearson chi-square Test for Association: χ^2=82.4 (p<. 001)

Table unbalanced due to ties and discrete scales (SKILL)

Table 12B: IT x WO (Using ITCAP and WO, respectively)

IT \ WO	Low	High
High	.00356 (.0179) N=448	.0664 (.0197) N=664
Low	0 (N/A) N=671	.00153 (.0199) N=442

Standard Error in parenthesis

Pearson chi-square Test for Association: χ^2=89.0 (p<. 001)

Table unbalanced due to ties and discrete scales (SKILL)

Table 12C: HK x WO (Using SKILL and WO, respectively)

HK \ WO	Low	High
High	-.0481 (.0208) N=492	.0372 (.0165) N=822
Low	0 (N/A) N=627	-.0522 (.0178) N=284

Standard Error in parenthesis

Pearson chi-square Test for Association: χ^2=211 (p<. 001)

Table unbalanced due to ties and discrete scales (SKILL)

Table 13: Correlations between manager's perception of IT effects with IT use, Human Capital and Decentralization

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 (ITCAP)	.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 (HKI)	.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

Notes

[1] There are a number of reviews of the growing empirical literature. See the symposium in the Spring, 1997 issue of the Journal of Economic Perspectives, especially Johnson [1997].
[2] See Autor, Katz and Krueger [1997] for 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] Murphy and Welch [1993] show percentiles of the wage distribution of prime-age males: the interquartile range has increased from about 1.75 to 1 to about 2.25 to 1. More extreme percentiles have moved even farther from the median, so that the entire distribution of wages is widening over time.
[4] The shift in labor demand precedes the shift in relative wages because of supply shifts. The baby boom's graduation from college, for example, was a supply event that transitorily depressed the wage premium for higher education in the 1970s. See Karoly [1996] and Juhn, Murphy and Pierce [1993].
[5] Clearly, parts of the shift in labor demand are explained by such broader economic patterns as globalization and sectoral shifts in employment. Yet these forces appear too small to explain the breadth and depth of the shift. See Krugman and Lawrence [1993].
[6] This is any invention which shifts the demand for more skilled vs. less skilled workers. Related concepts are capital-skill complementarity [Griliches, 1969], complementarity between skill and high technology capital [Berndt, Morrison, and Rosenblum,1992] and technology-skill complementarity [Berman, Bound and Griliches, 1994].
[7] Worker-level results are surveyed in Gottschalk [1997]. See also Juhn, Murphy and Pierce [1993], Bound and Johnson [1992] and Murphy and Welch [1993].
[8] Many of these studies treat broader measures of technological progressivity at the firm level than merely IT, with a variety of results. This includes Doms et al. [1997] and Dunne et al. [1997] for the US, and Aguirrebriria and Alonso-Borrega [1997] for the U.K. For France, Berman, Bound and Machin [1998], Duget and Greenan[1997], Bensaid, Greenan and Mairesse [1997] and, Greenan and Mairesse [1999] treat computerization at the firm level.
[9] The IT-intensive industries have seen the demand shift earlier [Wolff, 1996] and to a larger extent [Autor, Katz and Krueger, 1997] than other industries. A very interesting discussion of a wide variety of empirical papers looking at all three levels of aggregation may be found in Chennels and Van Reenen [1998].
[10] Among the first to predict this effect were Leavitt and Whisler [1958]. There are by now many papers treating the role of IT-enabled organizational change at varying levels of detail, notably Milgrom and Roberts [1990], Brynjolfsson, Renshaw and van Alstyne [1997], Bresnahan and Greenstein [1997], and Brynjolfsson and Hitt [1997]. This issue has also been extensively discussed in the managerial literature relating to business process redesign [Davenport and Short, 1990] and Hammer [1990].
[11] 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], Scott Morton [1991], Steiner and Teixera [1991], and Zuboff [1988].
[12] This stands in contrast to the other two complements, changed organization and improved products or services. We leave out software as an observable, taking improved systems to be closely related to either higher sales or better organization.
[13] This finding comes not only from the case study literature but also from systematic statistical work on investment in computer systems [Ito, 1996], on migrations to new kinds of computer architectures [Bresnahan and Greenstein, 1997] and on the private return to investments in IT [Brynjolfsson and Hitt 1996].
[14] The best known example of this type of software is produced by SAP (www.sap.com).
[15] The introduction of bar code scanners to supermarkets saved labor by cashiers. However, this benefit was vastly outweighed by the benefit of analyzing scanner-derived product data to improve inventory control, supply-chain management, marketing and promotion programs, and pricing strategies.
[16] Computer departments themselves employ highly skilled people to make computers useful.
[17] Bartel and Lichtenberg [1987] suggest that high levels of cognitive skills may be particularly important in creating and adapting to change, notably in implementing new technology. The managerial side of computer-based production processes is an excellent example of this story. The constant improvements in computer technology mean that organizations that use IT intensely have this demand for high levels of cognitive skill on a standing basis, not just for a single transition.
[18] See Bresnahan [1997] for more detail on the likely role of personal computers in driving labor demand.
[19] 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/.
[20] See Huselid [1994]; Ichniowski, Shaw and Prennushi [1997]; and Osterman [1994].

[21] These data were collected in three waves. A total of 416 firms provided at least some data for the study, including 93 from the first survey, conducted in Summer, 1995, 138 from a survey administered in Fall, 1995 and 199 from a survey in Summer, 1996.

[22] 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 our Fall, 1995 survey asked about the uniformity of work practices. For the average responding firm, organizational practices are 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.

[23] 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.

[24] For instance, we do not have any data on changes in outsourcing which might plausibly change the skill mix of remaining employees. Nor do we attempt to catalog and measure all the types of internal reorganization that might occur. Omitting these other forms of organizational change probably leads us to understate the role of organizational factors.

[25] 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, Osterman's [1994] survey (see footnote 23) found that 49.1% of the establishments in his sample 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 which also reflects increased decision-making by line workers.

[26] Another potential source of error in this regard is the outsourcing of computer facilities. To the extent that the computers are located at the firm site, they will still be properly counted by CII's census, but equipment at the outsourcer's other locations will be missed.

[27] 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.

[28] 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].

[29] Other explanations can also predict the covariances [Athey and Stern, 1998] but one would quickly discard a complementarities story if the covariances were absent from the data.

[30] 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.

[31] See Brynjolfsson and Hitt [1997] for more detail on the empirical relationship between IT and workplace organization.

[32] See Brynjolfsson and Hitt [1997] for more detail on the empirical relationship between IT and workplace organization.

[33] We get much the same story when we interact SKILL and WO with time dummies, not trends.

[34] There is something of an irony that decentralization of the organization (WO) and centralized computing (MIPS) are complements. However, this is a central fact of the technological history of our sample period [Bresnahan and Greenstein, 1997]. Only more recently has the organizational significance of PCs grown with the rise of the within-company networks as well as the Internet, browser-based organizational applications, and "downsized" organizational computing.

[35] WO is a bad way to take managerial rents, as it is a decentralization, not a centralization, of power to managers. ΔWO is a bad way to take any rents, as organizational changes like that are notoriously difficult and unpleasant.

[36] This is essentially the view that Ichniowski et al. [1996] put forth in their summary of the literature on innovations in workplace organization.

[37] Accordingly, it is not a criticism to note a weaker correlation between WO and IT in the early part of the sample (since our WO data are only contemporaneous with IT at the end of the sample period). Similarly, it is not an econometric criticism that WO(1995) is a measure of WO(t) with an error that declines over time; rather, this econometric remark is closely linked to the economics of our interpretation.[38] Four year lags were chosen to be sufficiently long to examine long-term effects, but short enough to minimize data loss in our sample.

[39] In fact, if current levels of computerization are used as a regressor, but not instrumented with past levels, the coefficient is substantially lower (not shown).

[40] Or it might simply reflect the fact that both COMP and HKI were drawn from the same survey, improving the match of the unit of observation, while the instrument, lagged IT, comes from the CII data.

[41] Cf. Milgrom and Shannon [1994] for a definition that goes beyond marginal analysis.

[42] Cf. Milgrom and Shannon [1994] for a definition that goes beyond marginal analysis.

[43] See for instance Kemerer and Sosa [1991] for a catalog of disastrous IT projects, many of a substantial financial size. Additional references to the difficulty of managing complex IT-enabled organizational change efforts appear in footnotes 10 and 11.

[44] Collinearity occasionally affects the estimates: worker skill and college education are not significant when included in the same regression with (an unusually large) IT interaction terms, although they are significant when entered separately (not shown).

[45] We have dropped the college education variant because it involves a substantial decline in sample size and this analysis presses the available variation in the sample quite hard. We dropped the professionals variant because it is a subset of the information workers variant. Fuller tables including the alternatives may be found in Bresnahan, Brynjolfsson and Hitt [1998].

[46] Cf. Brynjolfsson and Hitt [1997] or Brynjolfsson and Yang [1997].

[47] The coefficients for HK, WO and the components of all interactions are standardized to mean zero, standard deviation 1. The 12% number is calculated using the point estimates from Table 10, column 6: .0254*1+.0268*1+.0253*1*1+.00662*1*1+.0319*1*1+.00442*1*1*1=12.04%

[48] One can, of course, construct a more intricate theory to explain the results. In this case, there could be correlated shocks to the productivities of the factors at the firm level that are 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.

[49] This economic argument is one that Athey and Stern [1998] work to make more structural by using a switching regimes model of firm choice between distinct clusters.

[50] This economic argument is one that Athey and Stern [1998] work to make more structural by using a switching regimes model of firm choice between distinct clusters.

[51] In earlier work, we have conducted case studies and interviews inside many of the firms in our present sample, which is an important part of the background to our interpretation of the econometric evidence.