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## Productivity and the PC Revolution

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# 1. Introduction

Is there a ‘new economy,’ and if so, what has it brought? In 1951, Remington-Rand introduced the first commercially available mainframe computer (the UNIVAC) and in the process ushered in the modern computer age.<sup>1</sup> Over the last half century, computers have evolved from large, complex, very expensive, and as a consequence, rare machines to inexpensive and seemingly ubiquitous devices that even children can effectively operate. The widespread diffusion of this technology has engendered many debates over the societal ramifications of computer technology and its complements. In the economics literature, much of the discussion has focused on two related questions: what is the effect of computers on productivity, and how has the diffusion of computers changed the distribution of wealth? At the root of these queries is the following issue: Are computers fundamentally different from other types of technologies, and if they are different, how should this fact affect our thinking about the workings of the economy?

Most of the research prior to the early 1990s indicates that computers have a negligible effect on productivity (e.g. Morrison and Berndt (1991), Solow (1987), Brynjolfsson (1993)). More recent work (Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995)) has found that information technology (IT) investment increases output; they do not suggest that the impact of IT is different from other types of inputs. However, from 1995 until the present, productivity growth has dramatically increased and the timing of this growth spurt coincides with the expansion (both in number of users and in the number of websites) of the Internet. The timing of these phenomena has led some economists to conclude that computers have changed how we should think about the economy (Jorgenson (2001)).<sup>2</sup> In contrast, Gordon (2000) argues that the claims that computer technology is the new economic dynamo are overstated (e.g. David (1990)). He analyzes aggregate data and concludes that the productivity effects of computers is limited to the durable goods manufacturing sector and centered primarily in the computer producing industries.

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<sup>1</sup> An interesting note for economists is that one of the key innovations that led to the development of the UNIVAC was the central processing unit, which was conceived by Jon Von Neumann.

<sup>2</sup> Also see Greenspan (1997) and Brynjolfsson and Hitt (2000b).

In this paper we focus on the role of computers and information technology in affecting the productivity of panel of Fortune 1000 manufacturing firms from 1986-1993. This data contains detailed information on the IT investments by these corporations. Over this period, the typical firm invested heavily in IT. The information technology capital stock per employee of a typical firm increased from \$4,000 per worker to over \$27,000 per worker. Our main finding is that this accelerated investment in information technology generated increases in productivity greater than would be suggested by their cost share of inputs for the durable goods manufacturing sector. Based on the cost share information, the increase in IT should increase labor productivity 0.4%. However, we estimate that the increased investment in IT and in particular the increased use of the personal computer actually lead to a much greater increase in labor productivity—we find that IT increased labor productivity on average 1.3% per year. Importantly, IT does not have the same effect for the non-durable goods sector. IT investments appear to have little effect on productivity in that sector. Thus, the microeconomic data at the firm level roughly supports Gordon's macroeconomic findings.

Our data also contain detailed information on many different components of IT capital stock (e.g. personal computers, mainframes, storage devices) that allows us to further decompose the productivity consequences of IT usage. The data indicate that the use of personal computers is associated with these additional increases in labor productivity attributable to IT investment. Our estimates indicate that the growth in PC use in the durable goods sector increased labor productivity by 0.8% per year above and beyond the increase due to IT capital deepening.

The paper has the following structure. The next section briefly summarizes the previous work of the effect of computers on productivity. Section 3 describes our data and Section 4 outlines our empirical strategy. The results are presented in Section 5. Section 6 concludes.

## **2. Productivity and the Computer Revolution**

As investment in IT capital accounts for an ever-increasing share of capital investment, it is important to understand how these investments might pay off. Research on the impact of IT on productivity has been conducted mainly at two levels of analysis: the aggregate level focusing on

the economy and on industry sectors, and disaggregate levels including the firm and its underlying processes. Questions at the aggregate level that have been addressed examine the whether productivity – labor or multi-factor productivity (MFP) - in an industry or country has grown commensurate with IT investment, while at the disaggregate level, studies have examined impacts on process outputs, on firm profits and market value, in addition to productivity. Most studies at both levels of analysis have focused on productivity levels; recently the important question of the impact of IT on productivity growth has begun to be addressed (Brynjolfsson and Hitt 2000, Jorgenson 2001).

At the aggregate level, the most recent study is by Jorgenson (2001) who analyzes the impact of the price declines in IT on productivity growth. He suggests that there is an emerging consensus that it is the behavior of IT prices that underlies the recent rapid increase in economic output. He finds that productivity growth has been faster in IT-producing industries relative to IT-using industries. Moreover, he shows that these industries have accounted for roughly half of the recent surge in productivity growth. Another view is expounded by Gordon (2000) who finds that most of the productivity growth resides mainly in the computer producing industries.

In order to understand the overall impact of IT at the firm level, it is useful to begin by thinking about the qualitative impacts of introducing IT into a firm's production processes. Past research has characterized the impacts of IT as automating, informing and transforming (Zuboff (1988)). Automating impacts are primarily the direct substitution of capital for labor, consistent with capital deepening. For example, a cashier at a retail chain store using a computer based information system such as a scanner can process a transaction in less time. Informing impacts are those where an information system provides information that allows decision makers to make more effective decisions. To stay with the above example, information provided by the store-based system allows the firm to make better inventory decisions, which may increase total factor productivity at the firm level. Transforming impacts occur when a firm re-engineers a process to achieve significantly higher levels of productivity. In our example, the firm may redesign their supply chain using a supply chain management system, of which the store system is a key element.

A key difference between IT and traditional forms of capital, such as industrial equipment, is of course, the information processing capability of IT capital, in addition to production capabilities that are common to both forms of capital. In the information systems literature, this has often been referred to as its dual roles: as a production technology and as a coordination technology (Malone, Yates and Benjamin 1987, Gurbaxani and Whang 1991). These papers suggest the importance of organizational transformation to realize the full benefits of information technology. Brynjolfsson and Hitt (2000a) articulate the role of organizational co-investments in driving productivity growth.

While there is considerable anecdotal and case study evidence of a payoff from computers, the empirical evidence is much less clear. At the firm level, studies of the impact of IT on productivity have produced mixed results. Generally speaking, studies that use more recent data have found evidence of a relationship between IT and productivity, while studies that have used less recent data have usually not found such a relationship. For example, Barua, Kriebel and Mukhopadhyay (1995) examine the impacts of IT investment on intermediate business processes and on final outputs. Their results indicate a positive association of IT with intermediate process outputs, but show that IT has no effect on final output. Likewise, Loveman (1994) finds no impact of IT investments on output. On the other hand, Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995) analyzed the productivity impact of IT in a sample of 380 large firms. Both find a positive and significant output elasticity for IT; notably their estimates of output elasticity exceed its cost of capital.

The study most closely related to the present study is Brynjolfsson and Hitt (2000), who also focus on estimating the contribution of IT to growth. In addition, they introduce an important dimension to this research stream, the role of organizational co-investments. In order to examine how longer-term investments in these complementary factors affect changes in the contribution of IT, they vary the time horizon in the growth calculation. Their analysis is conducted on a sample of 600 large firms over the time period 1987 – 1994. They find evidence of a significant relationship between IT and MFP growth. Further, they find that the short-run contribution of IT to output “is approximately equal to the direct user cost of computer capital” while the long-run

contribution to implied marginal product and growth rises by an economically significant margin. They attribute this rise to the introduction of complementary productivity-enhancing organizational changes carried out over several years.

### 3. Empirical Framework

Our goal is to estimate the productivity impact of IT investments. There is a large body of literature devoted to the econometrics of productivity analysis that suggests there are many different approaches to estimating the relationships of interest. From this literature we employ two complementary approaches—each method requires different assumptions for the identification of the relationships of interest.<sup>3</sup> In the first approach, we estimate the parameters of a Cobb-Douglas production function and then explore the implications of those parameters for the productivity of IT. In the second approach, we examine the relationship of the Solow residual to factor inputs. Under constant returns to scale and perfect competition, the Solow residual should be uncorrelated with inputs. Therefore, examination of the correlations of the Solow residual with inputs is a test of the joint hypotheses of constant returns to scale and perfect competition. In estimating the parameters of interest in both approaches we use a dynamic, panel data methodology suggested by Arellano and Bond (1991).

#### A. Production Function Estimation

We model the value added of a firm to be a function of technology, its capital stock (excluding IT capital), its employment of labor inputs, and its use of IT capital. More specifically, letting  $i$  index firms and  $t$  index time,

$$VA_{it} = F(K_{it}, L_{it}, IT_{it}, t) \quad (1)$$

where  $VA_{it}$  is the value added (sales minus the expenditure on intermediate inputs),  $K_{it}$  is the non-IT capital stock,  $L_{it}$  is the number of employees, and  $IT_{it}$  is the stock of information technology capital.

Imposing the Cobb-Douglas functional form on (1) and taking logarithms gives

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<sup>3</sup> Brynjolfsson and Hitt (2000a) use a similar strategy.

$$va_{it} = m_{it} + \alpha k_{it} + \beta l_{it} + \gamma it_{it}, \quad (2)$$

where lower case variables denote logarithms. The variable  $m_{it}$  is multifactor factor productivity (MFP). Without the loss of too much generality we can decompose MFP into firm specific shocks and shocks common to all firms,

$$m_{it} = m_i + g_i t + e_{it}, \quad (3)$$

$m_i + g_i t$  is a firm specific mean and average growth productivity that is transmitted to the input choice and  $e_{it}$  is the innovation that may or may not be transmitted to the input choice. Taking differences of (2) and substituting in (3) in for MFP gives us the equation we apply to the data,

$$v\dot{a}_{it} = \alpha \dot{k}_{it} + \beta \dot{l}_{it} + \gamma \dot{i}_{it} + g_i + e_{it}, \quad (4)$$

where the dot superscript denotes time differences.

If firms differ only in their mean level of productivity, then  $g_i = 0$  for all  $i$ , so that lagged values of the inputs and twice-lagged (or greater values) of output would be valid instruments. If  $g_i$  does not equal 0, then either we must difference (4) or use a fixed-effects approach in order to generate consistent estimates of the parameters. As Griliches and Mairlesse (1984) point out, differencing is an unattractive option as it deletes much of the information from the data. Standard fixed-effects approaches are also problematic as this method transforms the dependent and independent variables by subtracting the mean of those variables where the mean is calculated using data over the entire sample period. This standard transformation implies that the variables are functions of the instrument set thereby invalidating them as instruments. Thus, we will consider the following forward-mean transformation (Arellano and Bond (1991)).

$$v\dot{a}_{it}^* = \alpha \dot{k}_{it}^* + \beta \dot{l}_{it}^* + \gamma \dot{i}_{it}^* + e_{it} \quad (5)$$

where

$$x_{it}^* = \left( \frac{T-t}{T-t+1} \right)^{1/2} \left( x_{it} - \frac{1}{T-t} \sum_{s=t+1}^T x_{is} \right).$$

In the analysis we estimate (4) with and without correcting for the fixed effect using forward differencing. Forward-mean differencing transformations leave the validity of the instrument set

intact. The parameters and the standard errors are estimated using a Generalized Method of Moments procedure (GMM).

Cobb-Douglas technology implies that cost share of inputs are equal to the elasticity of output (e.g. the production function parameters). If we observe, say,  $\gamma > s_{IT}$ , where  $s_{IT}$  is the cost share of IT capital then it most likely suggests three non-exclusive possibilities. Those possibilities are: there is some non-convexity in IT (network externalities, adoption of alternative organizational structures), we have mis-specified the functional form for the production function, or there are unobserved inputs that are correlated with the observed inputs.

## B. Solow Residual

The preceding estimation methodology relies heavily on the assumption of Cobb-Douglas technology. It is well known that while the Cobb-Douglas seems to fit production data in many circumstances, it also imposes a strong functional form on the data. An alternative approach to measuring the impact of IT investments is one that relies on examining the correlations of the Solow residual and the IT inputs. This approach dispenses with the strong functional form assumptions of Cobb-Douglas technology. However, the Solow residual methodology can only explore the joint hypothesis of constant returns to scale and perfect competition.

In our framework the Solow residual is defined to be:

$$\theta_{it} = v\dot{a}_{it} - \sum_{j \in \text{inputs}} s_{ji} \dot{x}_{j,it} \quad (6)$$

where  $s_{j,it}$  is the value added weighted cost share index of input  $j$ . A positive relationship between IT investments and the Solow residual implies that IT investments leads to productivity gains above and beyond what would be implied by a model based on linear-homogeneity of inputs and perfect competition. The intuition behind this result is straightforward. The observed share of an input, given the assumptions on competition and constant returns to scale, is an exact measure of the elasticity of the production function. With this elasticity in hand the rate of productivity growth is calculated by differencing the increase in input use times its output elasticity from the increase in output. As Hall (1988) points out, this residual should be orthogonal to all variables that do not affect MFP. As contemporaneous input usage is likely affected by productivity shocks we need to instrument for the contemporaneous input, and we use lagged values of the inputs as

instruments. Under the maintained hypotheses, the projection of lagged inputs and twice-lagged outputs on current inputs should be orthogonal to the Solow residual. Thus, in the instrumental variable (IV) framework a positive relationship between the growth rate of IT and  $\theta_{it}$  is a rejection of the null of perfect competition and constant returns to scale.

In order to calculate the Solow residual we need to formulate measures of the cost share of inputs. For variables that measure flows (i.e. labor) this is straightforward as the cost of the input for that period is simply the price of the input times the amount of the input that is used. However, for stock variables (i.e. non-IT and IT capital) the per-period rental rate must be imputed. The shares are calculated from the data by averaging cost shares over the current and previous period. In calculating the cost share of non-IT capital we follow the methodology proposed by Berndt and Fuss (1986). In calculating the cost share of IT capital we use the input prices assumed by Brynjolfsson and Hitt (2000a).

Once we have calculated the Solow residual,  $\theta_{it}$ , we regress it on the differenced log IT and variables that reflect the firm's IT investments (value of IT investments, PCs, MIPS, and Mainframes). We use an IV approach (both with and without forward-mean differencing) to estimate these relationships.

### C. Durable and Non-Durables Industries

We focus on large firms in manufacturing industries. We do this for two reasons. First, removing service industries from the sample reduces product heterogeneity. Second, output measurement for manufacturing industries is much more straightforward than for non-manufacturing industries.

We divide our sample of manufacturing firms into two sectors, durable and non-durable goods, performing the analysis separately for each sector. Gordon (2000) has argued that the productivity impact of IT is limited to the durable goods sector of the economy. Dividing our data into the two sectors allows us to examine whether Gordon's argument at the macro level holds in the micro-level data. Moreover, dividing the data into these two sectors enables us to explore the differences computerization may have on firms using different production processes. In particular, we note that the labor-capital ratio is substantially higher in durable goods industries.

Generally speaking, to the extent that the production of durable goods usually requires more sophisticated design and engineering processes and involves more rapid obsolescence than non-durable goods, this sector likely requires, on average, a more highly skilled work force. With the rapid decentralization of computing power to the desktop, it is certainly plausible that applying IT capital in the form of PCs and engineering workstations to knowledge work is likely to result in significant productivity gains. Furthermore, in many cases, the manufacture of non-durable goods can require larger investments in plants and equipment relative to durable goods. Comparing the results across these two sectors should reveal some insights into the processes by which firm level investments in computerization affect productivity.

#### **4. Data Sources**

Our data come from two primary sources: Compustat and Computer Intelligence InfoCorp (CII). We use the Compustat data to gather information on sales, capital stock, employees, cost of materials, R&D for the Fortune 1000 companies. The companies' primary Standard Industrial Classification (SIC) code is used to assign the company to either manufacturing or non-manufacturing firms. For this study, we kept only manufacturing firms (i.e. those firms with SIC codes between 20-40). The SIC code is also used to assign companies to durables and non-durable industries of the manufacturing sector. Durable goods industries are defined to be those assigned to SIC code greater than 31.

The Compustat data was matched to data collected by CII. CII conducts a series of surveys that tracks specific pieces of computer equipment in use at approximately 25,000 sites at different locations of the 1000 largest firms in the US. CII surveys managers of information systems to obtain detailed information on each site's IT hardware. CII checks on hardware that was reported in previous interviews in order to take hardware usage over time and check the reporting consistency. Each piece of hardware is assigned a market value, and these estimates are aggregated to form a measure of the total hardware capital. CII does not track software and thus it is missing from the measure of IT capital stock. Clearly, this is an important omission. Estimates indicate that expenditures on software (including maintenance and new development) are 25% less than on hardware (Gurbaxani (1990)) and the ratio is constant over time. Taken together with

the exponential price decline in hardware, Gurbaxani (1987) shows that the ratio of the stock of software to the stock of hardware declines exponentially over time. This implies that in so far as our IT capital measure understates the true IT capital stock, it does so by decreasing amounts. As the data rather accurately reflect the physical capital stock of IT at the firm, we believe that assumptions regarding depreciation and capital retirement rates are not needed.

Our data is from the period 1986 to 1993 – a period of rapid growth in the use of IT and therefore a period of interest. The quality of the CII data deteriorates substantially after 1994 as CII has undergone several acquisitions and changed its data gathering methodology. Unfortunately, we cannot use CII data to examine productivity in the post-1994 period in which the expansion of the Internet may have had substantial impacts on the productivity of IT.

For the analysis we removed firms with extreme values of IT capital to sales and non-IT capital to sales ratios. These deletions, which were few, left us with an unbalanced panel of 580 firms. The sample is roughly divided between durable and non-durable goods producing firms. There are 276 firms classified as producing durable goods and 304 firms classified as producing non-durable goods. Durable sector firms are somewhat larger than their non-durable counterparts as measured by employees (33,300 versus 21,808) and value added (\$1.9B versus \$1.8B).

## **5. IT Usage Across Firms and Time**

Table 1 presents the mean levels of the IT variables (per-employee) from 1986 to 1993 for the firms in our sample. Table 1 also presents these variables for the durable and non-durable sectors. There has been substantial deepening in IT capital over the period. Across all firms in our data, mean IT capital increased from \$4,400 to almost \$25,000 per employee. Moreover, these data suggest that there are significant differences between firms in the durable and non-durable sectors in their usage of computers. Firms in durable goods industries started the period with somewhat more IT capital and experienced a more substantial increase in IT capital relative to non-durable goods firms over the period. IT capital increases five fold in durable goods industries while increasing by a factor of 4.25 in the non-durable sector.

PC usage follows a similar pattern to IT capital. In 1986, PCs were relatively uncommon; the mean across all firms is one PC per every 20 employees. By 1994 PCs are ubiquitous, and there is one PC for every 4 employees. PC usage also differs across firms in the two sectors as computer power became more diffused across employees. Firms in the durable goods sector began the period using more PCs (0.05 versus 0.04 per employee) and these firms increased their usage at a greater rate (five-fold versus a 4.5-fold increase). The data also show that there was considerable substitution away from mainframe computers and the rates of substitution differ across the two sectors. Across all firms, the mean is 0.43 mainframes per 1,000 employees in 1986 and declined to 0.27 per 1,000 employees by 1994. In 1986, durable goods sector firms used mainframes more intensely than their non-durable goods sector counterparts (0.49 per 1,000 employees versus 0.39 per 1,000 employees); however by the end of our sample period there is very little difference in mean mainframes per 1,000 employees across the sectors.

The computational power residing within the firm grew even more dramatically than the increase in IT capital. MIPS per employee increased from 0.005 to 0.215 over the sample period. It should come as no surprise that MIPS increased at a much greater rate than IT capital as the price per MIPS dropped substantially over this period. The growth rate differs substantially across firms in the two sectors. Firms in the durable goods sector start the sample with an average of 66% more MIPS than firms in the non-durable sector. In 1994, durable goods firms have increased the number of MIPS per employee 40.2 times, while firms in the non-durable sector increased their computational power 17.6 times.

In Table 2 we present the growth rates of the IT variables. Typically, IT capital grew between 22 and 46 percent per year. With the exception of 1987, a year in which PCs grew at 52%, PC use increases approximately 20% per year. The typical growth rate in MIPS is approximately 40% per year. Table 2 also shows the effect of the 1991 recession on IT capital accumulation. IT capital actually declined 15% and this year also shows the slowest increase in PC usage.

Table 3 presents the inter-quartile ranges of the IT variables across firms at the beginning of the sample and at the end of the sample. There are two messages that can be deduced from Table 3. First, within each sector, there is a large amount of variation in the IT variables and the

distributions of all of these variables across the durable and non-durable sectors overlap. Second, a few firms do not drive differences in the means of the IT variables across firms in the durables and non-durable sectors discussed above. All quartiles, both at the beginning and at the end of the sample, show high IT usage in the durable goods sector.

Table 4 presents the correlations between the growth rates of the IT variables. In general, the correlations between the variables are modest. The highest correlation is between the growth rate of IT capital and the growth rate of MIPS at 0.47. The correlations between the growth rates of the other variables range from 0.15 to 0.28. The modest magnitude of the correlations suggests that these variables represent distinct choices for the firms and these variables are not all measures of the same phenomena.

Table 5 presents the input shares as a percentage of value added. In general, expenditures on IT capital are dwarfed by expenditures on labor and non-IT capital. IT capital is, on average, 0.7% of value added, while labor is, on average, 68% and non-IT capital expenditures is 13% of value added. However, IT's share increased over the period from 0.4% in 1986 to 1.3% in 1993. The durables sector has a higher share of IT use than the non-durable sector which is not surprising given the previous tables, On average, IT's share in the durable sector is approximately 35% greater (0.84% versus 0.63%) than in the non-durable sector. There is very little difference across the two sectors in the growth of IT's share over the sample period. In Table 5, we also see differences across the sectors in input usage. The durable goods sector is more labor intensive than the non-durable sector. The labor share is, on average, 75% and capital's share is 10% for the durable sector; while in the non-durable sector labor is 58% and the capital share of capital is 15%, on average.

To summarize this section, our data has shown that firms have rapidly expanded their use of IT and the computing power residing in the firm has dramatically increase over our sample period. Firms have also decentralized their computer infrastructure, substituting away from mainframes to personal computers. However, IT remains, at least in 1994, a small percentage of inputs used by firms. Importantly, there appears to be large differences across firms in the durable and non-durable sectors in their capital stock of IT and use of personal computers. This suggests

that IT affects the production differently in these sectors. In the next section we explore this issue in greater detail.

## **6. Information Technology, Personal Computers and Productivity**

In this section we present our estimates of the parameters of the production function and the correlations between IT use and the Solow residual. We begin though, by examining the correlations between the growth rate of our IT variables and the growth rate of labor productivity and the Solow residual (see Table 6). Across all firms in the sample there is little evidence of a positive relationship between IT investments and these productivity measures. There is a moderate correlation (0.09) between the growth rate of PCs and the growth rate of labor productivity. In the Solow residual regression there is a similarly modest correlation (0.10) between the Solow residual and the growth rate in MIPS. Other than these two variables the correlations of the other variables are very close to zero. For durable goods there appears to be a stronger relationship between the productivity variables and the growth rate of IT variables. For both the growth rate of labor productivity and the Solow residual the correlations between growth rate of IT and the growth rate in PC use is positive. In particular, the correlations between these productivity measures and the growth rate of PCs are both 0.16. For the firms in the non-durable goods sector all the correlations between the productivity measures and the growth rate of the IT variables are all very close to zero. The raw correlations suggest that there is a difference between the durable and non-durables sector in the effect of computer investments on productivity and that PCs seem to be a determinant of productivity..

In Table 7 we present the GMM estimates of the production function, equation (4), for all firm in the sample. Table 8 presents the same parameter estimates for the durable goods sample and Table 9 presents these coefficients for the non-durables sample. All of these tables present both the parameter estimates with and without forward-mean differenced fixed-effects and for each set of panel data methodologies we estimate parameters for three different specifications where the set of IT capital variables differs across the specifications. For discussion purposes we focus on the parameter estimates for the fixed-effects results as the estimates without fixed-effects are similar.

The parameter estimates for the entire sample indicate a moderate impact of IT on value added. In particular, the coefficient on PC usage is significantly different from zero with five percent confidence, and in all specifications the coefficient on IT capital is positive and large relative to its cost share; however it is not precisely estimated. The coefficient on non-IT capital looks reasonable but the coefficient of labor is implausibly small. Blundell and Bond (1999) argue that production function estimates are likely to suffer from downward bias and the labor parameter estimate is consistent with their claim.

In Table 8 we present the production function estimates for the durable goods sector. The parameter estimates on the IT variables are larger than the parameter estimates generated using the entire sample. In Column 3 of the fixed effects estimates, we present the production function estimates including PCs and MIPS in addition to IT capital. The coefficient on IT capital is large (0.049) and reasonably precisely estimated (s.e.=0.024). Recall that the value added share of IT capital reaches its maximum at 0.015 in this sample, and that under the assumption of Cobb-Douglas production technology the share of an input should equal its parameter value in the production function. Thus, the point estimate of IT capital parameter is over 3 times the theoretical value implied by its cost share. PC usage appears to have an impact on productivity above and beyond its effect through IT capital. The coefficient on PC is 0.031 with a standard error of 0.019 and it is significantly different from zero at the 10% level of confidence.<sup>4</sup> Hansen's (1982)  $\chi^2$  test of the validity of the instruments does not reject the over-identifying restrictions.

Using the cost share information for the durable goods sector, the predicted growth rate in labor productivity over this period due to the deepening IT capital stock is 0.4%. The parameter estimates from the production function imply that labor productivity increased at 1.3% due to the increase in the IT capital stock. Even if our IT measures understates the true capital stock by 50%, our estimates would still imply that IT capital substantially impacts labor productivity more than implied by its input usage. The parameter estimates also imply that the increase in PC use

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<sup>4</sup> Gordon (2000) argues that most of the increase in productivity in the durable goods sector due to IT investment is primarily limited to the computer manufacturing industries. We removed the computer manufacturing firms from the durable goods sector sample and re-estimated the production function parameters. The fundamental results are invariant to this robustness check.

accounted for an additional 0.8% of the growth rate in labor productivity above the contribution of the IT capital stock (which includes the stock of PCs) for the durable goods sector. As discussed in section 2, there is a view that the productivity impacts of IT are due, in part, to complementarities between the organizational form and technology. In so far as PCs allow for different information flow within the firm through the decentralization and networking of computing power, complementarities between PCs and skilled labor, and organizational transformation, our findings support this view.

In contrast with the results in Table 8, the results in Table 9 indicate that IT usage has little impact on firms in the non-durable sector. The IT coefficients are all very small with standard errors larger than the coefficients themselves. Theoretically, we expect the parameters of IT capital to be small as the cost shares of IT capital are particularly small in this sector. However, unlike the results for the durable sector there is no evidence that IT is impacting output more than would be predicted by its share.

Tables 10,11 and 12 present the relationships between the growth rate of the IT capital variables and the Solow residual for the entire sample, the durable goods sector and the non-durable sector, respectively. Here we present the results with and without controlling for fixed effects in the specification.

The pattern that emerges from the Solow residual regressions is very similar to the pattern in the parameters from the production function estimates. In Table 10, using data from the entire sample, there is a non-trivial correlation between the growth rate of PCs and the Solow residual, and there is little correlation between the other IT variables and the Solow residual. However, in the analysis using firms from the durable goods sector, when included separately as dependent variables, the coefficients on the growth rate of IT capital and PCs are positive, reasonably large in magnitude and precisely estimated. When both IT variables are included simultaneously as independent variables (along with the growth rate of MIPS), the coefficients on these variables are also positive and large in magnitude and reasonably precisely estimated. Thus, for the durable goods sector we can reject the joint hypotheses of perfect competition and constant returns to scale. This finding, in conjunction with the previous set of results strongly suggests that the

important source of this rejection is that there are increasing returns to IT investment. Finally, we note that the test of the over-identifying restrictions does not reject the validity of the instrument set.

In contrast, the regressions of the Solow residual on the growth rate of IT capital for the non-durable goods sector does not yield coefficients that could be interpreted as a rejection of the joint hypotheses of perfect competition and constant returns to scale.

## **7. Conclusion**

In sum, we find that IT investments appear to impact different sectors of the economy differently. The growth rate of IT capital and in particular the increased use of personal computers affects productivity more than would be predicted by their input share in the durable goods sector. However, we find little impact of IT investments in the non-durable sector. These findings raise an obvious question: What is it about durable goods production *vis-a-vis* the non-durable sector that allows IT to have large impacts on productivity? That is a question that hopefully will be addressed by future research.

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**Table 1**

Mean Levels of Information Technology Variables per Employee

Year	All Firms				Durables				Non-Durables			
	IT (\$1,000)	PCs	MIPS	Main Frames (per 1,000)	IT (\$1,000)	PCs	MIPS	Main Frames (per 1,000)	IT (\$1,000)	PCs	MIPS	Main Frames (per 1,000)
1986	4.4	0.05	0.004	0.43	4.8	0.05	0.005	0.49	4.0	0.04	0.003	0.39
1987	6.1	0.08	0.006	0.45	6.6	0.10	0.007	0.50	5.6	0.07	0.005	0.39
1988	6.7	0.11	0.009	0.43	7.6	0.12	0.011	0.48	5.8	0.10	0.007	0.39
1989	7.8	0.13	0.020	0.38	9.0	0.14	0.032	0.43	6.6	0.11	0.010	0.33
1990	11.5	0.15	0.026	0.34	12.9	0.16	0.037	0.39	10.0	0.13	0.016	0.30
1991	11.1	0.19	0.049	0.37	12.8	0.20	0.072	0.40	9.6	0.17	0.025	0.33
1992	16.9	0.21	0.100	0.30	20.4	0.24	0.166	0.32	13.2	0.18	0.033	0.27
1993	24.9	0.25	0.137	0.27	28.8	0.28	0.215	0.26	21.0	0.22	0.058	0.27

**Table 2**

Mean Growth Rates of Information Technology Variables

Year	All Firms				Durables				Non-Durables			
	IT	PCs	MIPS	Main Frames	IT	PCs	MIPS	Main Frames	IT	PCs	MIPS	Main Frames
1986	---	---	---	---	---	---	---	---	---	---	---	---
1987	0.23	0.52	0.34	0.01	0.22	0.55	0.37	0.04	0.23	0.49	0.30	-0.01
1988	0.07	0.39	0.38	-0.02	0.08	0.42	0.39	-0.02	0.05	0.35	0.36	-0.02
1989	0.22	0.19	0.51	-0.19	0.19	0.16	0.62	-0.20	0.25	0.23	0.39	-0.17
1990	0.40	0.19	0.43	-0.12	0.38	0.17	0.48	-0.18	0.42	0.21	0.37	-0.06
1991	-0.15	0.16	0.40	0.00	-0.16	0.14	0.40	0.01	-0.14	0.18	0.40	-0.02
1992	0.39	0.18	0.41	-0.13	0.40	0.19	0.49	-0.15	0.37	0.18	0.32	-0.11
1993	0.46	0.17	0.37	-0.12	0.45	0.17	0.42	-0.15	0.47	0.17	0.33	-0.09

**Table 3**

## Inter-quartile Distribution of Information Technology Variables

Variable	All Firms			Durables			Non-Durables		
	25%	50%	75%	25%	50%	75%	25%	50%	75%
1986-1987									
IT/L (\$1,000)	2.4	4.0	6.4	2.5	4.5	6.9	2.2	3.6	5.6
PC/L	0.02	0.04	0.08	0.03	0.04	0.08	0.02	0.04	0.07
MIPS/L	0.002	0.003	0.006	0.002	0.004	0.007	0.002	0.003	0.005
Main Frames /L (per 1,000)	0.2	0.3	0.5	0.2	0.4	0.6	0.2	0.3	0.5
1992-1993									
IT/L (\$1,000)	8.8	17.0	29.2	11.1	19.5	34.0	7.6	15.1	25.5
PC/L	0.10	0.18	0.32	0.11	0.20	0.34	0.08	0.15	0.31
MIPS/L	0.02	0.04	0.11	0.03	0.06	0.20	0.01	0.02	0.06
Main Frames /L (per 1,000)	0.07	0.2	0.3	0.08	0.2	0.3	0.05	0.2	0.3

**Table 4**

## Correlation of Growth Rates in Information Technology Inputs

Variable	All Firms		Durables		Non-Durables	
	%Δ IT	%Δ MIPS	%Δ IT	%Δ MIPS	%Δ IT	%Δ MIPS
%Δ IT	1.00	0.47	1.00	0.45	1.00	0.49
%Δ MIPS	0.47	1.00	0.45	1.00	0.49	1.00
%Δ PC	0.24	0.19	0.29	0.21	0.18	0.16
%Δ Main Frames	0.23	0.20	0.21	0.15	0.25	0.28

**Table 5**

## Mean Input Shares of Value Added

Year	All Firms			Durables			Non-Durables		
	Labor	Non-IT Capital	IT	Labor	Non-IT Capital	IT	Labor	Non-IT Capital	IT
1987	0.68	0.12	0.004	0.83	0.11	0.005	0.55	0.14	0.003
1988	0.65	0.12	0.004	0.75	0.10	0.005	0.56	0.13	0.004
1989	0.64	0.13	0.005	0.73	0.10	0.006	0.57	0.15	0.005
1990	0.66	0.14	0.006	0.73	0.10	0.008	0.61	0.16	0.006
1991	0.69	0.15	0.007	0.75	0.11	0.009	0.64	0.17	0.007
1992	0.70	0.14	0.009	0.74	0.10	0.011	0.67	0.18	0.010
1993	0.65	0.14	0.013	0.70	0.10	0.015	0.66	0.18	0.009

**Table 6**

## Correlation of Growth Rates in Information Technology Inputs and Productivity Measures

Variable	All Firms		Durables		Non-Durables	
	% $\Delta$ Labor Productivity	Solow	% $\Delta$ Labor Productivity	Solow	% $\Delta$ Labor Productivity	Solow
% $\Delta$ IT	0.03	0.03	0.09	0.07	-0.02	0.01
% $\Delta$ MIPS	0.01	0.10	0.02	0.02	-0.02	0.01
% $\Delta$ PC	0.09	0.01	0.16	0.16	0.02	0.04
% $\Delta$ Main Frames	-0.00	0.01	0.02	0.01	-0.02	0.02

**Table 7**

GMM Estimates of Production Function Parameters, Total Sample  
(standard errors)

	No Fixed Effects			Forward Differenced Fixed Effects		
	(1)	(2)	(3)	(1)	(2)	(3)
Capital	0.238 (0.043)	0.229 (0.043)	0.232 (0.043)	0.265 (0.057)	0.253 (0.058)	0.249 (0.058)
Labor	0.436 (0.053)	0.460 (0.054)	0.447 (0.054)	0.356 (0.061)	0.377 (0.064)	0.374 (0.064)
IT	0.040 (0.012)		0.024 (0.015)	0.021 (0.015)		0.020 (0.017)
PC		0.026 (0.012)	0.020 (0.012)		0.031 (0.015)	0.029 (0.015)
MIPS		0.017 (0.008)	0.009 (0.009)		0.003 (0.009)	-0.004 (0.011)
R <sup>2</sup> -adj	0.226	0.226	0.227	0.008	0.007	0.007
$\chi^2$ (p-value)	0.143	0.124	0.180	0.066	0.093	0.091
Obs.	2,304	2,304	2,304	1,820	1,820	1,820

Dependent variable is the growth rate of value added; all dependent variables are in growth rates. Instrument set includes the contemporaneous and lagged values of the dependent variables and the lagged value of the growth rate of value added. Regressions also contain annual dummies which are not reported.

**Table 8**

GMM Estimates of the Production Function Parameters, Durable Sector

	No Fixed Effects			Forward Differenced Fixed-Effects		
	(1)	(2)	(3)	(1)	(2)	(3)
Capital	0.264 (0.054)	0.247 (0.055)	0.268 (0.054)	0.291 (0.072)	0.289 (0.073)	0.289 (0.073)
Labor	0.499 (0.080)	0.532 (0.081)	0.494 (0.080)	0.437 (0.104)	0.460 (0.107)	0.436 (0.105)
IT	0.053 (0.016)		0.048 (0.020)	0.043 (0.020)		0.049 (0.024)
PC		0.038 (0.015)	0.026 (0.016)		0.040 (0.018)	0.031 (0.019)
MIPS		0.006 (0.010)	-0.008 (0.012)		-0.007 (0.012)	-0.019 (0.014)
R <sup>2</sup> -adj	0.366	0.363	0.368	0.210	0.203	0.210
$\chi^2$ (p-value)	0.714	0.338	0.846	0.594	0.555	0.400
Obs.	1,152	1,152	1,152	915	915	915

Dependent variable is the growth rate of value added; all dependent variables are in growth rates. Instrument set includes the contemporaneous and lagged values of the dependent variables and the lagged value of the growth rate of value added. Regressions also contain annual dummies which are not reported.

**Table 9**

GMM Estimates of the Production Function Parameters, Non-durable Sector  
(standard errors)

	No Fixed Effects			Forward Differenced Fixed Effects		
	(1)	(2)	(3)	(1)	(2)	(3)
Capital	0.188 (0.068)	0.189 (0.070)	0.189 (0.070)	0.164 (0.087)	0.157 (0.089)	0.157 (0.090)
Labor	0.383 (0.069)	0.392 (0.070)	0.388 (0.070)	0.324 (0.074)	0.335 (0.077)	0.334 (0.077)
IT	0.023 (0.016)		0.010 (0.021)	-0.000 (0.018)		-0.018 (0.024)
PC		0.009 (0.015)	0.007 (0.017)		0.013 (0.023)	0.014 (0.023)
MIPS		0.016 (0.011)	0.012 (0.014)		0.012 (0.014)	0.020 (0.018)
R <sup>2</sup> -adj	0.138	0.139	0.138	-0.167	-0.166	-0.168
$\chi^2$ (p-value)	0.348	0.299	0.227	0.160	0.147	0.122
Obs.	1,152	1,152	1,152	897	897	897

Dependent variable is the growth rate of Solow residual added; all dependent variables are in growth rates. Instrument set includes the contemporaneous and lagged values of the dependent variables and the lagged value of the growth rate of Solow residual. Regressions also contain annual dummies which are not reported.

**Table 10**

GMM Solow Residual Estimation: Total Sample  
(standard errors)

	No Fixed Effects				Forward Differenced Fixed Effects			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
IT	0.029 (0.012)			0.011 (0.016)	0.020 (0.015)			0.018 (0.018)
PC		0.027 (0.012)		0.022 (0.012)		0.0360 (0.014)		0.033 (0.014)
MIPS			0.0168 (0.0076)	0.011 (0.009)			0.007 (0.010)	-0.002 (0.012)
R <sup>2</sup> -adj	0.046	0.046	0.045	0.047	-0.259	-0.250	-0.250	-0.252
$\chi^2$ (p-value)	0.033	0.041	0.031	0.056	0.006	0.029	0.004	0.015
Obs.	2,304	2,304	2,304	2,304	1,820	1,820	1,820	1,820

Dependent variable is the growth rate of Solow residual added; all dependent variables are in growth rates. Instrument set includes the contemporaneous and lagged values of the dependent variables and the lagged value of the growth rate of Solow residual. Regressions also contain annual dummies which are not reported.

**Table 11**

## GMM Solow Residual Estimation: Durable Sector

	No Fixed Effects				Forward Differenced Fixed Effects			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
IT	0.032 (0.016)			0.031 (0.021)	0.039 (0.021)			0.045 (0.025)
PC		0.028 (0.015)		0.022 (0.016)		0.034 (0.017)		0.028 (0.017)
MIPS			0.003 (0.010)	-0.010 (0.012)			-0.002 (0.010)	-0.018 (0.014)
R <sup>2</sup> -adj	0.105	0.104	0.099	0.106	-0.194	-0.196	-0.200	-0.196
$\chi^2$ (p-value)	0.351	0.377	0.164	0.378	0.219	0.273	0.895	0.359
Obs.	1152	1152	1152	1152	915	915	915	915

Dependent variable is the growth rate of Solow residual added; all dependent variables are in growth rates. Instrument set includes the contemporaneous and lagged values of the dependent variables and the lagged value of the growth rate of Solow residual. Regressions also contain annual dummies which are not reported.

**Table 12**

## GMM Solow Residual Estimation: Nondurable Sector

	<u>No Fixed Effects</u>				<u>Forward Differenced Fixed Effects</u>			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
IT	0.016 (0.016)			-0.006 (0.022)	0.001 (0.018)			-0.021 (0.026)
PC		0.013 (0.016)		0.014 (0.016)		0.029 (0.023)		0.028 (0.023)
MIPS			0.017 (0.011)	0.019 (0.015)			0.013 (0.014)	0.023 (0.020)
R <sup>2</sup> -adj	0.020	0.020	0.020	0.019	-0.323	-0.323	-0.320	-0.326
$\chi^2$ (p-value)	0.191	0.163	0.263	0.166	0.116	0.175	0.142	0.129
Obs.	1,152	1,152	1,152	1,152	897	897	897	897

Dependent variable is the growth rate of Solow residual added; all dependent variables are in growth rates. Instrument set includes the contemporaneous and lagged values of the dependent variables and the lagged value of the growth rate of Solow residual. Regressions also contain annual dummies which are not reported.