Information technology and its impact on productivity: firm-level evidence from government and private data sources, 1977-1993

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1. Introduction

Robert Solow's quip that "we see computers everywhere but in the productivity statistics" has prompted a large and growing literature examining the *Information Productivity Paradox*. Some aggregate and industry-level studies have failed to detect a positive contribution to productivity growth from investments in computer technology.[1] More recent studies utilizing firm-level data, however, have detected a significant contribution.[2] This paper confirms the results of these latter studies using U.S. firm-level computer asset and financial data for non-agricultural firms during the period 1977-1993 from a variety of data sources including the U.S. Census Bureau's Enterprise and Auxiliary Establishment Surveys, Compustat, and Computer Intelligence Infocorp, a market research firm.

Our principal finding, that computers--especially personal computers--do contribute positively to productivity growth, suggests that the traditional *Information Productivity Paradox* is largely a measurement problem. This is closely related to the more general problem of assessing service sector productivity, because computers are used most intensively in the service sector and in the 'service' functions of non-service sector firms (e.g., payroll and purchasing). As Zvi Griliches (1994) noted, these activities pose the greatest problems for output and productivity measurement. Moreover, although we may see computers everywhere, they represent only a tiny fraction of capital stock (on about 2% of plant, property and equipment), so aggregate effects may be hard to detect (Oliner and Sichel 1993).

Our data indicate that computers not only contributed to productivity growth during the period 1977-1993, but they yielded *excess returns* relative to other types of capital. The data also suggest that computer productivity peaked around 1986/1987,[3] that computers are complementary with skilled labour (Krueger 1993 and Autor, Katz and Krueger 1997), and that use of computers may permit reductions in inventory levels. Finally, and perhaps most interesting, the evidence

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indicates that the *types* of computers and how they are used makes an important difference (Landauer 1995): *personal computers* appear to have an especially large impact on productivity. This finding highlights the importance and difficulty of measuring computer inputs accurately.

We interpret data on the number of PCs or PCs per employee as providing an indication of the extent of usage of computers within the firm. Firms that had more PCs per employee would be expected to be using computers more broadly across the organization (and, presumably, have a higher percentage of computer-literate employees), which may account for their higher productivity. In the near future, once virtually everyone has a computer on his or her desk, data on the number of PCs per employee will be less informative and we will need to collect even more detailed firm- or business-unit-level data in order to accurately measure the contribution of computers.

The rest of this paper is divided into four sections. In section 2 we present our econometric (production function) model. Section 3 describes our data sources and summarizes broad patterns of computer usage. Estimates of the model are reported in section 4, and section 5 gives a summary and conclusions.

2. The model

The essence of the 'productivity paradox' is, that while we seem to have been investing heavily in computers for quite a number of years[4], the rate of measured productivity growth has failed to increase, and may have even decreased. Since productivity is defined as output per unit of input, and computers are an input, we should start by asking under what conditions one would expect growth in computer intensity to raise productivity.

The contribution of computers to productivity growth may be *disembodied* or *embodied*. The embodied approach hypothesizes that output (Y) is an exponential function of factor inputs of capital (K) and labour (L) times a multiplicative technology parameter (A), which yields the following Cobb-Douglas production function: $Y = A\ K^{á}\ L^{1\text{-}á}$. In this formulation, total factor productivity (TFP) is defined as follows:

$$TFP \equiv \frac{Y}{K^{á}\ L^{1-á}} = A. \tag{1}$$

According to this view, computers contribute to productivity by raising A, which makes all factor inputs proportionately more productive. Computers might have this effect if their principal function were to improve coordination. It is also possible that computers may contribute to technical progress directly because they are more productive than other types of factor inputs. One way to represent embodied technical progress is to model production as:

$$Y = A[K_0 + (1 + è)K_1]^{á}L^{1\text{-}á} \tag{2}$$

where total capital (K) is decomposed into computer capital (K_1) and non-computer capital ($K_0 \equiv K - K_1$), á is the elasticity of output with respect to the 'effective' capital stock [$K_0 + (1 + \text{è})K_1$], and è is a parameter that measures the 'excess productivity' of computer capital (K_1) relative to non-computer capital (K_0). After re-arranging and taking logs, equation (2) can be expressed as:

$$\ln Y = \ln A + \text{á} \ln K + \text{á} \ln(1 + \text{è} * IT\%) + (1 - \text{á}) \ln L \qquad (3)$$

where $IT\% \equiv (K_1 / K)$ is the share of computer capital in the total capital stock. This implies the following forms for *TFP* and Labour Productivity (*Y/L*):[5]

$$\ln TFP \cong \ln A + \text{áè} * IT\%, \text{ and} \qquad (4)$$

$$\ln\left(\frac{Y}{L}\right) \cong \ln A + \text{á}\ln\left(\frac{K}{L}\right) + \text{áè} * IT\%. \qquad (5)$$

Equation 4 reveals that increased computer-intensity (*IT*%) would be expected to increase total factor productivity only if computers are more productive than other types of capital.[6] Under the null hypothesis of zero excess returns to computer capital,[7] the first order conditions for profit maximization require that the ratio of the marginal products of computer to non-computer capital be equal to the ratio of the user costs of capital for computer to non-computer capital, or:

$$\frac{MP_{K_1}}{MP_{K_0}} = (1 + \text{è}) = \frac{R_1}{R_0} = \frac{(r + \text{ä}_1 - E(p_1))P_1}{(r + \text{ä}_0 - E(p_0))P_0} \qquad (6)$$

where *MP* is the marginal product, *R* is the user cost of capital, *r* is the risk-adjusted discount rate, ä is the depreciation rate, *P* is the purchase price per unit of capital, and $E(p)$ is the expected rate of price appreciation. A sub 1 indicates that the variable is for computer capital while a sub 0 indicates that it is for noncomputer capital. The ratio of the user cost of computers to other types of capital ought to be in the range of from 3 to 6.[8] To be conservative, we use a figure toward the outside limit of this range in formulating our null hypothesis that there are no excess returns associated with computers:

$$H_0\text{: No excess returns} \Leftrightarrow \text{è} = 5 \qquad (7)$$

Under this null hypothesis, *TFP* and (*Y/L*) will not depend on the share of computer capital, except perhaps because of its effect on disembodied technical progress (via A, which will be captured by the fixed year and industry/firm-level effects in our regression analyses).

If computers are more productive then other types of capital, *TFP* and (*Y/L*) will increase with the share of computer capital, but the effect will be attenuated by capital's overall expenditure share, á, which is typically estimated to be on the order of 20-30%. The small size of á implies that total factor productivity and labour productivity will be relatively insensitive even to changes in overall capital intensity.

Many popular discussions of productivity focus on labour productivity rather than *TFP*. One interpretation of the 'productivity paradox' is that, in the last two decades, *IT*% has accelerated but (*Y/L*) has declined. But equation (5) indicates that labour productivity depends on overall capital intensity (*K/L*) as well as on the *composition* of capital (*IT*%), so this finding would not be paradoxical if capital deepening had decelerated. This is indeed the case: the growth rate of (*K/L*) declined from 3.0% in 1948-73 to 2.0% in 1973-79 to 1.3% in 1979-90. The stock of computer capital may have been increasing rapidly (although high gross investment is largely offset by rapid depreciation of computers), *but the growth in the stock of other capital has been quite sluggish*.

The true structure of production is much more complicated than is indicated by the above. For example, labour is heterogeneous and output is also a function of intangible capital (generated by past R&D investment). This implies that the right-hand-side variables included in equation (3) are a very incomplete subset of the entire list of determinants of productivity. This increases the probability that the so-called productivity paradox is an *ecological fallacy*: the apparent lack of a simple correlation between computers and productivity in aggregate data should not lead us to infer that computers have not 'paid off.' To accurately assess the marginal productivity of computers, it is necessary to analyze microeconomic data, especially firm-level data, as Brynjolffson and Hitt (1993), Lichtenberg (1995), and others have done.

There is another reason (emphasized by Oliner and Sichel, 1993) to believe that using aggregate productivity data to attempt to assess the returns to computer investment may be like searching for a needle in a haystack: even today, computer capital is a small share of total capital. To illustrate this point, it is useful to consider a slightly different version of the production function:

$$\ln Y = \acute{a}_0 \ln K_0 + \acute{a}_1 \ln K_1 + (1 - \acute{a}_0 - \acute{a}_1) \ln L. \qquad (8)$$

In growth rates, this becomes,

$$Y' = \acute{a}_0 K_0' + \acute{a}_1 K_1' + (1 - \acute{a}_0 - \acute{a}_1) L' \qquad (9)$$

where Y' denotes the growth rate in Y, etc. The contribution of computer growth to output growth is $\acute{a}_1 K_1'$. Moreover, in equilibrium, the elasticity of output with respect to computers should be equal to the marginal productivity of computers times the computer-to-output ratio, or $\acute{a}_1 = MP_1(K_1/Y)$. Even if the marginal productivity of computers is very high and computer capital has grown rapidly, K_1/Y is still small (on the order of 2%) and so $\acute{a}_1$ is quite small.[9] Therefore, the contribution to aggregate output growth would be small.

Another reason why we may fail to measure productivity gains from computers is that there may be substantial time lags before gains are realized. Paul David (1990) argues that computers may require substantial changes in complementary infrastructure (e.g., human and knowledge capital, global communications infrastructure, etc.) before the gains to them may be realized.

The longitudinal and cross-sectional depth of the data presented here offers a viable method for addressing these concerns. Moreover, by examining data in five year increments, we reduce problems associated with transient fluctuations.

Failure to adequately capture quality improvements is another important source of measurement error that tends to bias downwards estimates of returns to computer investment (Siegel 1994). If prices accurately reflect quality changes, using sales as a measure of output will help correct the problem, but typically, prices do not fully reflect quality improvements. A large share of the benefits accrue to consumers without being measured either in higher unit sales or industry revenues. Bresnahan (1986) attempted to address this problem by estimating the total social returns to computer investment. This approach allowed him to impute substantial social returns to computer investment. Ceteris paribus, the implication of this effect for our results is to bias them downwards since we do not attempt to measure the effect on consumer surplus.

Perhaps offsetting the above bias is the danger that an increased share of computer capital is positively correlated with an unobserved input that is more directly responsible for the increased output. Computer capital may be positively correlated with labour quality (i.e., the share of skilled workers). Suppose output varies not only with capital quality ($IT\%$), but also labour quality (y) as follows:

$$\ln TFP \cong \ln A + \text{áè} * IT\% + (1 - \text{á})\text{ð}y \qquad (10)$$

where y is the share of employment that is skilled. If we fail to take account of the dependency of output on y, then we will obtain biased estimates of á if $IT\%$ and y are correlated. In section 4, we find evidence of a positive correlation between computer use and education (and wages), which suggests that (K_1/L) and y are positively correlated. The correlation between $IT\%$ and y will depend also on the level of capital intensity since $(K_1/L) = (K_1/K)(K/L) = (IT\%)(K/L)$. If we hypothesize that the correlation between $IT\%$ and y is given by ã (i.e., $IT\% = \text{ã}y + \text{å}$), then we can estimate the upward bias as:

$$p\text{limá}^* = \text{á} + \text{ã}(1\text{-á})\text{ð}. \qquad (11)$$

The most direct solution to this problem is to include a measure of labour quality among the regressors. We follow this approach when possible.

Finally, there is a danger that our measure of computer capital (i.e., the replacement value of computer hardware) systematically underestimates computer inputs because it fails to reflect investments in software, training, or other computer-related expenditures. Suppose that equation 4 is the correct model but our estimate of the share of computer capital ($IT\%$) is too low by half. In that case, our estimate of *áè* would be too high by a factor of two.[10] Alternatively, one might question whether measuring computer inputs in current prices adequately reflects the investment in embodied technical progress.[11]

We attempt to control for measurement and omitted variable problems in four ways. First, firm fixed effects control for time-invariant (or slowly-changing) unobserved variables. Second, wherever possible, we have attempted to include additional regressors to control for potential determinants of productivity that may be correlated with computer intensity. This includes the share of auxiliary employment in total employment, the number of establishments, and alternative measures of the composition of computer assets (e.g., the share of large systems that are mainframes, and the total number of personal computers). Third, by utilizing data from multiple, diverse sources, we are able to partially cross-validate our results. Fourth, we adopt a conservative specification for the null hypothesis regarding excess returns which will help offset any errors due to an understatement of the appropriate share of computer capital in total assets.

3. Data description and trends

In the following two subsections we describe our data and then explore trends and other indicators of how computer usage has changed over our sample period.

3.1 Data Description

This study utilizes a mixture of public and private data on the diffusion and utilization of computers by large firms assembled from four major sources and a variety of ancillary sources covering the period 1977-93 (see table 1). Unlike a number of earlier firm-level studies which considered only manufacturing firms, over 50% of the total employment for our sample is in non-manufacturing firms (see tables 3 and 4). Our data are split into two longitudinal panels, the first covering the period 1977-87 and the second covering the period 1986-93.

For the 1977-1987 period, we use U.S. Bureau of the Census data from the Enterprise Survey (ES) and the Auxiliary Establishment Survey (AUX) for 3 to 4 thousand firms, accounting for over 20 million employees.[12] The ES provides enterprise-wide financial data, while the AUX provides similar establishment-level data for all of a firm's auxiliary establishments.[13] Auxiliary establishments are non-production facilities housing what may be thought of as the ‘service-sector’ functions of the firm. These include administrative headquarters, R&D facilities, sales offices, warehouses, etc. Each of these surveys is conducted every five years and our sample includes data for 1977, 1982 and 1987.

The AUX data are especially interesting because of our focus on business computing (rather than factory automation). Most of a firm’s support services--which contribute to what is generally referred to as ‘corporate overhead’--are likely to be housed in auxiliary establishments. These data allow us to examine the effect of computers on firm organization, as measured by the distribution of activity and employment. Because the auxiliary establishments perform ‘service-sector’ functions for the firm, they offer an opportunity to investigate how computers affect service sector productivity. Additionally, the AUX data provide detailed information bearing on the composition of non-production staff workers in six categories of employment: (1) central administrative and clerical, (2) research and development (R&D), (3) warehousing, (4) sales and sales support, (5) electronic data processing (EDP), and (6) other auxiliary employment. This allows us to partially control for labour quality.

TABLE 1
List of major data sources

Enterprise Survey (Census Bureau)
Enterprise Surveys for 1977, 1982 and 1987 offer data on computer investments (but not computer assets) and other balance sheet and income statement variables for 6,000 to 8,000 firms.
Auxiliary Establishment Survey (Census Bureau)
Auxiliary (i.e., non-production) Establishment Surveys for 1977, 1982 and 1987 offer data on computer investments (but not computer assets), other balance sheet and income statement variables, and employment by occupation for 31,000 to 38,000 auxiliary establishments.
Computer Intelligence Infocorp
Company-level data (derived from site-level survey) for 1986, 1991 and 1993 on computer assets, by type of computer, for 1,000 -1,400 large U.S. firms.
Compustat
Enterprise data for 1986, 1991 and 1993 for income statement, balance sheet and other financial variables for firms covered by Enterprise Survey and Computer Intelligence Infocorp data.

For each firm, we collected data on total sales (Y), the book value of plant, property and equipment (PPE or K), total investment (I), total investment in computers (I_1), and total employment (L). In addition, we collected data on the share of investment associated with auxiliary establishments, the share of PPE in auxiliary establishments, and the composition of auxiliary employment.

For the period 1986-93, we use data from the marketing research firm Computer Intelligence (CI) and Compustat. The CI data include detailed information about the composition of computer assets at Fortune 1000 and Forbes 400 firms for the years 1986, 1991 and 1993.[14] The computer information includes the estimated replacement cost of all computer assets (K_1), as well as detailed information on the composition of computer capital (e.g., counts of the number of systems of different types such as mainframes, minis and PCs; the total number of MIPS; the total volume of DASD; etc.). We linked the CI data with Compustat financial data, resulting in a data set with approximately 1,500 observations for 500 firms accounting for total employment of over 16 million.

Our use of both the Census and CI data allows us to consider a longer time period than would be possible with either source alone. Moreover, the partial overlap in 1986-87 allows us to investigate the relationship between computer investment and computer capital data and the relationship between both of these and output. Unfortunately, the only measure of computer inputs included in the Census data is the level of computer investment, which provides a noisy estimate of the computer share of total assets. We matched the Census and CI data for the years 1986/1987 for 757 firms[15] in order to estimate the relationship between the computer shares of investment and capital:

$$\frac{K_1}{K} = \acute{a} + \hat{a}\left(\frac{I_1}{I}\right). \qquad (12)$$

The estimated coefficients from this regression (see table 6) are used to ‘backcast’ the computer share of capital for the unmatched Census firms in 1987 and all of the Census firms in 1977 and 1982.[16]

3.2 Data trends

Over the 16 years covered by our data, the diffusion of computers into the fabric of American business has been dramatic. According to the Current Population Survey (CPS), the likelihood that an employee is using a computer in the workplace has nearly doubled from 1 in 4 in 1984 to almost 1 in 2 by 1993 (see table 2). A similar pace of diffusion is evident in the firm-level data from the Census Bureau and CI. From 1977 to 1987, computer investment per employee increased from approximately \$63 to \$267 in nominal terms, representing a nominal growth rate of 16% per year. Due to the more rapid depreciation rate for computer capital (20-30% per year), the growth in computer assets would have been slower.[17] A better indication of the diffusion of computer usage is provided by noting that in 1977, only 38% of the firms in our sample reported *any* computer investment, whereas 82% reported computer investments by 1987.[18]

The CI data offer a clearer picture of these diffusion trends. From 1986 to 1993, the mean replacement value of computer assets per employee increased from \$995 to \$1256 (see table 4). However, during this same period, computer intensity increased substantially if one considers performance-based measures. For example, MIPS per employee increased 11-fold, DASD capacity per employee increased almost 3 fold, and the mean number of PCs and terminals per employee increased from 1/4 to 2/3.[19] It is comforting to note how close these firm-reported figures are to those implied by the household data on work-based computer usage reported in table 2.

Even with this substantial growth, however, it is not surprising that computers appear to have failed to contribute to aggregate output growth. According to the

TABLE 2
Probability of using a computer at work[1] (Source: Current Population Survey)

	1984	1989	1993
Overall:	25	37	46
By education:			
<9th grade		3	4
9-11		10	13
12		29	34
13-15		46	53
16+		58	69
By household income:			
<$10K		18	18
$10-15K		20	24
$15-20K		28	32
$20-25K		35	36
$25-35K		39	43
$35-50K		48	51
$50-75K		53	62
>$75K		53	67
By occupation:			
Manag. & Professional		56	68
Tech Sales Admin		55	66
Service		10	15
Prec Prod Craft		15	23
Operators, Labour		10	15
Farm, Forest, Fish		4	9
By industry:			
Agriculture			14
Mining		31	46
Construction		13	17
Manufacturing		36	44
Trans, Comm, Util		40	49
Wholesale/retail		28	37
Finance, Insurance		8	79
Services		39	48
Forest/Fisheries		38	38
Public Admin		62	74

[1] The Current Population Survey (CPS) of Census Bureau is a household survey for years 84, 89, 91, 93 and includes responses to the question, "Did you use computer at work?" for 55,000 households.

CI data, the computer share of total assets is tiny (approximately 0.3% in 1993), and the share of Plant, Property and Equipment (PPE) was only 1% in 1993.[20]

In addition to the trend towards greater computer intensity in terms of both quality (as measured by the increases in computing power) and the level of financial commitment by the firm (as measured both by the levels of investment and computing capital), there was movement towards more distributed architectures as evidenced by the substantial growth in smaller systems (PCs and minicomputers), while the numbers of mainframe computers declined. This appears to be related to, and may have facilitated, the increased geographical dispersion of firms. According to the CI data, between 1986 and 1993, the median growth rate in the number of sites per firm was 46% and the median number of employees per site declined 27%.[21] The Census data provides additional indirect evidence of the move towards increased decentralization and distributed systems.[22] In 1977, 6% of the employment but 22% of the computer investment occurred in auxiliary establishments, whereas in 1993, 7% of the employment and only 6% of the computer investment occurred in auxiliary establishments.[23] Computer investments are more evenly distributed across the firm in the latter period (see table 3).

When firms are ranked by employment size, the larger firms tend to invest more per employee in computers, although the difference is small.[24] Moreover, the gap between larger and smaller firms appears to have narrowed over time.[25]

Cross-industry comparisons indicate consistent trends, although non-manufacturing sectors (*e.g.*, Services, FIRE) are more computer intensive than manufacturing. The cross-industry differences are consistent with computer usage data from the CPS (table 2). Similarly, within the firm, auxiliary establishments (the non-manufacturing, service-sector arms of firms) are more computer intensive. For example, auxiliaries account for 10% of employment but 33% of the computer investment in 1987. This is not surprising because the first uses for business computers were for R&D and for such back office support services as payroll and accounting -- activities associated with AUX establishments in our data.

While all types of workers are more likely to use computers today, there is a strong skills-bias toward the better educated, higher paid, managerial and professional workers (table 2).[26] The revolution in information technology may offer a partial explanation for the widening wage gap between skilled and unskilled workers. Computers and skilled labour are complementary (Krueger 1993; Autor, Katz and Krueger 1997). Our data on the relative computer intensity of auxiliary establishments, large versus small firms, and cross-industry comparisons (with more knowledge-intensive industries such as FIRE being more computer intensive) are consistent with these results.

As a final validation check, we examined the CI data on the composition of computer assets by regressing the total value of computer assets (K_1) against the

TABLE 3A
Census data on computer investment[1]

	1977	1982	1987
Number of firms	3,318	3,734	3,714
% which report:			
Computer investment>0	38%	70%	82%
Computer investment in auxiliary>0	23%	43%	48%
	Median Values		
Employment per firm	1,602	1,535	1,724
	$0	$28	$68
% employment in auxiliary	6%	6%	7%
% total investment in computers	0%	2%	3%
% computer investment in auxiliaries	22%	11%	6%
	Mean Values (unweighted)		
Employment per firm	6,180	5,865	6,339
Computer investment per employee	$63	$152	$267
% employment in auxiliary	8%	10%	10%
% total investment in computers	3%	6%	8%
% computer investment in auxiliaries	46%	39%	33%
Computer investment per employee (weighted by employment)	$129	$298	$339

TABLE 3B
Census Firms in Sample, by Industry

SIC Code (1-digit)		Percent of observations in sample[2]	Mean employment per firm (000s)
0	Agriculture	0.5%	18
1	Mining, Construction	4.0%	4
2	Manufacturing	23.4%	5
3	Manufacturing	23.3%	7
4	Transport, Comm, Utilities	0.8%	6
5	Wholesale and Retail Trade	33.4%	6
6	FIRE	-	-
7	Services	11.4%	9
8	Healthcare, Legal, Education	3.2%	5
	Total	100.0%	6

[1] For subset of firms in Enterprise Survey which report having Auxiliary Establishments.
[2] Because not all firms were present in all three years, this is only approximately equal to the share of firms in the sample.

TABLE 4A
Corporate computer utilization[1]

	1986	1991	1993
Number of Firms	455	501	533
Total Employment (000s)	16,119	16,301	16,747
		Median	
Employment per firm	14,783	13,285	13,051
Computer Assets per employee	$680	$516	$736
Mainframes per firm	5	3	2
MIPS per 1000 employees	3	19	33
DASD per employee	6	14	16
PCs and Terminals per employee	0.17	0.43	0.49
PCs per employee	0.03	0.13	0.17
Computer share of PPE	1.4%	0.8%	1.0%
Computer share of Total Assets	0.5%	0.3%	0.3%
		Mean	
Employment per firm	35,427	32,537	31,420
Computer Assets per employee	$995	$872	$1,256
Mainframes per firm	11	8	6
MIPS per 1000 employees	4	47	116
DASD per employee	11	26	32
PCs and Terminals per employee	0.24	0.57	0.66
PCs per employee	0.05	0.19	0.24
Computer share of PPE	2.5%	1.6%	2.1%
Computer share of Total Assets	0.7%	0.5%	0.6%

TABLE 4B
Computer intelligence firms in sample, by industry

SIC Code (1-digit)		Percent of observations in sample[2]	Mean employment per firm (000s)
0	Agriculture	-	-
1	Mining, Construction	4.9%	18
2	Manufacturing	27.8%	23
3	Manufacturing	28.5%	40
4	Transport, Comm, Utilities	11.2%	32
5	Wholesale and Retail Trade	10.4%	65
6	FIRE	14.7%	20
7	Services	1.7%	34
8	Healthcare, Legal, Education	0.7%	50
	Total	100.0%	33

[1] SOURCE: Computer Intelligence Enterprise-level data for Fortune 1000 firms.
[2] Because not all firms were present in all three years, this is only approximately equal to the share of firms in the sample.

number of mainframes, minicomputers, and PCs and terminals for 1986, 1991 and 1993 (see table 5). The coefficients for these regressions provide estimates of the mean replacement value for each type of equipment. First, note that the R^2 of these regressions declines over time, reflecting the fact that other types of equipment (*e.g.,* LANs and other types of data communications equipment) comprise a growing share of total computer investments. Second, note that while the median number of mainframes per firm has declined and the number of PCs and terminals has increased, there has been little change in the relative value shares of these types of equipment. Firms were not replacing mainframes with PCs, but rather replacing several older mainframes with a smaller number of more powerful mainframes *and* investing in PCs and terminals. Third, note that the computer asset shares and prices which we estimate with our CI data are similar to the value shares and prices reported in industry data for domestic shipments.[27]

4. Production function estimates

In the preceding section, we documented the dramatic increase in computer usage across all types of firms in all industries. We now ask whether these changes have contributed to productivity growth. To test this, we estimate Cobb-Douglas production functions in two basic forms:

$$\ln Y_{it} = \tilde{a}_t + \ddot{e}_i + \acute{a} \ln K_{it} + \acute{a}\grave{e} x_{it} + \hat{a} \ln L_{it} + \mu_{it} \quad (13)$$

and

$$\ln Y_{it} = \tilde{a}_t + \ddot{e}_i + \acute{a}_0 \ln K_{0,it} + \acute{a}_1 \ln K_{1,it} + \hat{a} \ln L_{it} + \mu_{it}. \quad (14)$$

The parameter $\tilde{a}_t$ measures disembodied technical change, $\ddot{e}_i$ is a fixed firm-effect (or in some cases, a fixed industry-effect) that captures stable, unobserved firm- (or industry-) specific determinants of productivity, and μ_{it} is a disturbance term.[28] The first of these equations follows from equation (3), while the second is a standard Cobb-Douglas production function generalized to include two types of capital: computer (K_1) and non-computer (K_0) capital. In the following three sub-sections, we present our estimates.

4.1 Estimating computer asset share from census data

As we noted earlier, the only measure of computer inputs included in the Census data is the level of computer investment. We therefore estimated the relationship between the computer share of Plant, Property and Equipment and the computer share of investment for a matched subset of firms that are included in both the CI and Census samples for 1986/1987 (table 6).[29] This also allowed us to assess how noisy a proxy the computer share of investment is for the computer share of assets. Computers contribute to productivity growth in (6.1) and (6.2), but the

TABLE 5

Composition of computer assets regressions[1,2]

Replacement Value Computers = α_1(# Mainframes) + α_2(# Minicomputers) + α_3(# PCs + Terminals)

	Regression Coefficients (Standard Errors)			Est. Share of Total Value of Computer Assets[3]			Domestic Shipments[4] 1991	
	1986	1991	1993	1986	1991	1993	Share	Avg. Unit Price
Mainframes	$927,928	$922,210	$1,873,866	40%	32%	38%	28%	$1,173,878
	(65,276)	(94,501)	(142,106)					
Minicomputers	$66,948	$24,346	$23,664	11%	16%	16%	25%	$54,522
	(11,708)	(2,720)	(2,189)					
PCs and Terminals	$1,795	$849	$920	49%	52%	46%	47%	$2,546
	(111)	(62)	(69)					
Mean Value of Computer Assets ($000s)	$20,605	$19,783	$27,086	100%	100%	100%	100%	
Number of observations	957	935	968					
R^2	0.85	0.76	0.73					

[1] In the regressions, the dependent variable is the replacement value of computer capital measured in current dollars. The independent variables are the number of mainframes, minicomputers, and PCs and terminals. The mainframe and minicomputer categories include a diverse range of machine types, but we did not have data on the composition of these categories. The data are from Computer Intelligence.

[2] Standard errors are in parentheses below estimates. All coefficients are significant at the 1% level.

[3] The share of computer asset value is computed by multiplying the mean count of each type of computer by its corresponding regression coefficient.

[4] SOURCE: Information Technology Industry Council, *Information Technology Industry Data Book, 1960-2007*, table 4-3.

t-statistic associated with (I_1/I) in equation (6.2) is much lower.[30] When both measures are included in equation (6.3), the coefficient of (I_1/I) is insignificant and the coefficient on (K_1/K) is essentially unchanged.[31]

TABLE 6
Census regressions[1,2]

Relationship between K_1/K and I_1/I with (K_1/K) = á + â (I_1/I) + e	á	â
	0.015[a]	0.097[a]

log(Sales) = á log(K) + â log(L) + ä(I_1/I) + ã(K_1/K) + e			
Regression equation	6.1	6.2	6.3
log(K)	0.346[a]	0.270[a]	0.345[a]
log(L)	0.545[a]	0.617[a]	0.547[a]
K_1/K	3.606[a]		3.541[a]
I_1/I		0.410[a]	0.281[c]
è*[3]	10.4		10.3

[a] denotes significant at 1% level, [b] denotes significant at 5% level, [c] denotes significant at 10% level.

[1] The computations were carried out using a matched sub-sample for 1987 with N = 757.

[2] *K* is PPE, *L* is employment, *I* is total investment, K_1 is replacement value of computer assets, and I_1 is computer investment.

[3] è* is the estimate of the excess productivity of computer capital, computed as the ratio of the estimated coefficient on K_1/K divided by the estimated coefficient on *logK*.

4.2 Computer productivity regressions

Table 7 includes our principal productivity regression results. First, notice that the computer variable is significantly positive in all of the pooled time-series regressions. Moreover, the magnitude of these regression coefficients demonstrates excess returns to computer capital using the test described in equation (7)[32] in all of the pooled regressions except equation (7.4). These findings suggest that the 'productivity paradox' is an artifact of econometric measurement error which disappears with suitably detailed, firm-specific data.

Second, notice that the coefficients on *K* and *L* are close to the typical expenditure shares and are reasonably stable across all of the regressions. We cannot reject the hypothesis of constant returns to scale for the first two regressions with industry effects.[33] Moreover, the coefficients for the computer variables in regressions (7.1) and (7.2) are remarkably close, despite the fact that these are estimated from two completely different data sets covering two different time periods.

TABLE 7
Production function regressions[1,2,3] for the model

Regression	$\log(sales) = \acute{a}_0 \log(K) + \acute{a}_1 IT\% + \hat{a}_0 \log(L) + e$:			
	7.1	7.2	7.3	7.4
Fixed effects for:	Census Industry	Computer Intelligence Industry	Census Firm	Computer Intelligence Firm
Years:	1977-1987	1986-1993	1977-1987	1986-1993
ln(K)	0.276[a]	0.293[a]	0.148[a]	0.249[a]
ln(L)	0.714[a]	0.602[a]	0.724[a]	0.532[a]
$IT\%$ (= K_1/K)	2.282[a]	2.261[a]	1.681[a]	0.808[b]
è[4]	8.3	7.7	11.3	3.2
N	10692	1487	10692	1487
R^2	0.9	0.92	0.98	0.99

Estimated Coefficients for Share of Computer Assets (*IT%*), by Year[5]:

	Estimated Coefficient on Share of Computer Assets	N	R^2	*è**[4]
1977	-1.02	3296	0.92	-4.1
1982	2.561[a]	3686	0.9	8.1
1987	3.063[a]	3708	0.9	12.1
1986	3.169[a]	453	0.91	13.1
1991	2.188	500	0.93	6.8
1993	1.078	532	0.93	3.6

[1] These computations were carried out using Census and Computer Intelligence Data for 1977-1993. All regressions include fixed year effects. Industry effects are 3-digit SIC codes for 1977-1987 and 4-digit for 1986-1993. [a] denotes significant at 1% level, [b] denotes significant at 5% level, [c] denotes significant at 10% level.
[2] The dependent variable is log of sales.
[3] K is Plant, Property and Equipment (*PPE*); L is Total Employment; and *IT%* is the share of computer assets in total *PPE*. Because we do not observe K_1 directly for the Census regressions, *IT%* is imputed or predicted using the share of investment in computers and the regression of the computer share of assets (dependent variable) against the computer share of investment (independent variable) for the matched sample of firms which appear in both the Census and the CI data in 1986/1987.
[4] è* is the estimate of the excess productivity of computer capital, computed as the ratio of the estimated coefficient on K_1/K divided by the estimated coefficient on log$K$.
[5] Includes industry fixed effects.

Third, when we introduce firm effects in (7.3) and (7.4), the computer coefficients are reduced, but still are sufficiently large to support a finding of excess returns. This suggests that there are omitted variables that are positively correlated with computer inputs and that also contribute to productivity growth. Obvious candidates include ‘knowledge capital’ and a higher quality labour force. We explore these possibilities further below.

Although we find the above results compelling, we might be falsely interpreting the direction of causality, namely, that productivity growth drives investment in computers.[34] Brynjolfsson and Hitt (1966) tried instrumental variables (IV)[35] as well as ordinary least squares (OLS). They report an even larger productivity contribution from computer capital with IV than with OLS. Also, the Hausman specification test failed to reject the null hypothesis that the error term was uncorrelated with the regressors.

In the second half of table 7, we show the estimate for the coefficient on the share of computer capital when the model with industry effects is estimated separately for each year.[36] These results suggest that computer productivity increased from 1977, reached a peak in 1986/1987, and then began to decline. This would be consistent with high adjustment costs initially[37] followed by rapid expansion of computer assets which would exhaust opportunities to realize excess returns from further computerization as firms approached the optimal level of computer capital. Alternatively, the insignificant coefficients in 1977, 1991 and 1993 may be due to increased measurement error. We have already discussed how the need to estimate (K_1/K) for 1977 using coefficients computed for 1987 is likely to have contributed to measurement error. The potential for increased measurement error during the latter period is less obvious, but might be attributable to an increasing share of unmeasured computer-related purchases (*e.g.*, investments in data communications equipment, software, and a variety of computer services such as maintenance, etc.) in total IT expenditure.

Table 8 presents various sensitivity tests using the Census data. Regression (8.1) replaces (K_1/K) with (I_1/I), yielding similar conclusions but less significant results. Regression (8.2) adds the share of employment in auxiliaries. The coefficient on (L_1/L) is significant, which suggests that auxiliary employees are more productive. However, their excess productivity is less than their wage differential, suggesting that they yield below normal returns.[38] Similar results are provided by regressions (8.5) and (8.6), which further decompose auxiliary employment into separate categories. Only Electronic Data Processing (EDP) employees yield excess returns relative to other types of workers.[39] Inclusion of these proxies for labour quality differences does not significantly affect the computer coefficient estimates, suggesting that computers are not simply proxying for unobserved labour quality differentials.[40]

TABLE 8
Production function regressions[1,2]

	7.1	7.3	8.1	8.2	8.3	8.4	8.5	8.6
Fixed effects for:	Industry	Firm	Industry	Industry	Industry	Industry	Industry	Industry
ln(*K*)	0.276[a]	0.148[a]	0.272[a]	0.272[a]			0.274[a]	0.272[a]
ln(K_3)					0.062[a]	0.059[a]		
ln(K_2)					0.230[a]	0.227[a]		
ln(*L*)	0.714[a]	0.724[a]	0.718[a]	0.719[a]	0.693[a]	0.699[a]	0.716[a]	0.719[a]
IT% (=K_1/K)	2.282[a]	1.681[a]		2.166[a]			2.194[a]	2.148[a]
IT2% (=K_1/K_2)					1.271[a]	1.220[a]		
y (=L_1/L)				0.328[a]		0.384[a]		
IT3% (I_1/I)			0.123[a]					
%EDP of L							1.849[a]	1.221[b]
%CAO of L								0.259[a]
%WHS of L								0.504[a]
%R&D of L								0.264
%Other of L								0.201[c]
%Sales of L								0.395
è*[3]	8.3	11.3		8.0			8.0	7.9
N	10,692	10,692	10,692	10,692	10,091	10,091	10,692	10,692
R^2	0.90	0.98	0.90	0.90	0.90	0.90	0.90	0.90

[1]All regressions are computed using census data for 1977-1987 and with Log(Sales) as the dependent variable. The equation estimated include fixed year effects. Industry effects are 3-digit SIC codes. [a] denotes significant at 1% level, [b] denotes significant at 5% level, [c] denotes significant at 10% level.

[2] *K* is Plant, Property and Equipment (*PPE*); K_3 is non-machinery and equipment *PPE*; K_2 is machinery and equipment; K_1 is computer assets; *L* is Total Employment; L_1 is Auxiliary Employment; *I* is Total Investment; I_1 is computer investment; %EDP is electronic data processing employment share of *L*; %CAO is central office administration employment share of *L*; %WHS is warehouse employment share of *L*; %R&D is research and development share of *L*; %Sales is sales and customer support employment share of *L*; and, %Other is remainder of auxiliary employment share of *L*.

[3] è* is the estimate of the excess productivity of computer capital, computed as the ratio of the estimated coefficient on K_1/K divided by the estimated coefficient on log*K*.

Finally, regression (8.3) and (8.4) decompose capital into machinery and equipment (K_2) and structures (K_0). These show that computers yield excess returns relative to other types of machinery and equipment.[41]

Table 9 presents analogous sensitivity results for the CI data as well as productivity estimates based on equation (14). Regressions (9.1) to (9.7) experiment with different ways of measuring computer assets. This new form for the production function requires a slightly different hypothesis test, but this new test also indicates that there are significant excess returns to computer capital, indicating robustness of our principal findings to alternative econometric specifications.[42]

Regressions (9.2) through (9.7) substitute *counts* of various computer types for the replacement value of computers; in all cases we find a significant contribution from computers. What is perhaps most interesting is the magnitude of the coefficient on the number of PCs and terminals. This coefficient is huge and highly significant. Moreover, the coefficient is unaffected by inclusion of MIPS and DASD (measures of computer capacity) and is much larger than the coefficient on mainframes. This suggests that raw computing power matters less than how computers are used.[43] More PCs means that computers are distributed more widely throughout the firm and that users are more likely to be on networks which allow them to take advantage of such applications as electronic mail.

Table 10 repeats regressions (9.1) and (9.7) by year. Regressions (10.1) through (10.3) provide further support for our finding that computer productivity seems to have peaked in 1986/1987 and declined thereafter. While the coefficients are all significant, excess returns are earned only in the first year. Regressions (10.4) through (10.6) show that the coefficient on PCs and terminals remains fairly constant and significant over the entire sample period. This suggests that the reduced productivity gains from computers are not associated with further deployment of PCs but may be due to excessive investments in maintaining legacy systems.

4.3 Inventory Regressions

Computers facilitate outsourcing and can enable 'just-in-time' inventories. Computers can also permit firms to design, manufacture, distribute and inventory a much wider selection of goods. If the first effect dominates, we would expect computers to reduce inventory levels. The second effect would tend to increase inventory levels. In table 11 we present regressions of the inventory-to-sales ratio against the computer share of PPE, controlling for firm size by including total PPE. In all of the regressions, across both the Census and CI samples, the point estimates on (K_1/K) are negative although not always significant.

Perhaps the most interesting of these regressions are those with fixed firm effects[44] for which results are shown in the columns labelled 11.3 and 11.4. In both cases, we find computers have a significant negative impact on inventory

TABLE 9
Production function regressions[1,2]

Regression	7.2	9.1	9.2	9.3	9.4	9.5	9.6	9.7
Log(L)	0.602[a]	0.570[a]	0.586[a]	0.505[a]	0.524[a]	0.589[a]	0.591[a]	0.505[a]
Log(K)	0.293[a]							
Log(K_0)		0.238[a]	0.247[a]	0.217[a]	0.222[a]	0.242[a]	0.245[a]	0.218[a]
IT% (=K_1/K)	2.261[a]							
Log(K_1)		0.077[a]						
Log(SYSTEMS)			0.063[a]					
Log(MAIN)				0.052[a]				0.053[a]
Log(MINIS)				0.007				0.010
Log(PCTERM)				0.129[a]	0.151[a]			0.136[a]
Log(MIPS)						0.054[a]		-0.007
Log(DASD)							0.048[a]	-0.003
R^2	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92

[1] The computations were carried out using Computer Intelligence data for 1986-1993 with N=1,487. The dependent variable for all of the estimated equations is Log(Sales). All regressions include fixed year and industry effects. Industry effects are 4-digit SIC codes. [a] denotes significant at 1% level, [b] denotes significant at 5% level, [c] denotes significant at 10% level.
[2] K is Plant, Property and Equipment (*PPE*, \$millions); K_0 is *PPE* which is not computers (\$millions); K_1 is value of computer assets (\$millions); L is Total Employment (000s); *SYSTEMS* is the number of mainframes (*MAIN*) plus minicomputers (*MINIS*); *PCTERM* is the number of PCs and terminals (000s); *MIPS* is the number of *MIPS*; and *DASD* are the megabytes of disk storage (000s).

levels. The estimated coefficient on computer capital in regression (11.4) suggests that an additional dollar of computer capital would allow the firm to have about \$0.38 less in total inventories (which represents a savings of about \$0.03 per year assuming an interest rate of 7%). The impact of computers is likely to be more dramatic in terms of how inventories are organized and managed, rather than on the dollar cost of those inventories.[45]

5. Conclusions

This paper has examined trends in computer usage and the effect on productivity growth for a cross-industry panel of firms during the period 1977-1993. We linked firm-level financial and computer asset data for non-agricultural firms from a variety of public and private data sources, including Census Bureau data from the Enterprise and Auxiliary Establishment Surveys, Compustat, and the

TABLE 10
Production function regressions[1,2]

	10.1	10.2	10.3	10.4	10.5	10.6
Year	1986	1991	1993	1986	1991	1993
Log(L)	0.548[a]	0.587[a]	0.586[a]	0.504[a]	0.526[a]	0.508[a]
$Log(K_0)$	0.128[a]	0.280[a]	0.276[a]	0.126[a]	0.265[a]	0.253[a]
$Log(K_1)$	0.168[a]	0.059[b]	0.039[c]			
Log(MAIN)				0.034	0.055	0.060[c]
Log(MINI)				-0.031	0.024	0.044
Log(PCTERM)				0.140[b]	0.151[a]	0.134[a]
Log(MIPS)				0.055	-0.076[b]	-0.047
Log(DASD)				0.019	0.013	-0.013
N	453	500	532	453	500	532
R^2	0.91	0.94	0.93	0.92	0.94	0.93

[1] All computations were carried out using Computer Intelligence Data for 1986-1993. The dependent variable for all of the estimated equations is *Log(Sales)*. All regression include fixed industry effects. Industry effects are4-digit SIC codes. [a] denotes significant at 1% level, [b] denotes significant at 5% level, [c] denotes significant at 10% level.
[2] *K* is Plant, Property and Equipment (*PPE*, $millions); K_0 is *PPE* which is not computers ($millions); K_1 is value of computer assets ($millions); *L* is Total Employment (000s); *SYSTEMS* is the number of mainframes (*MAIN*) plus minicomputers (*MINIS*); *PCTERM* is the number of PCs and terminals (000s); *MIPS* is the number of *MIPS*; and *DASD* are the megabytes of disk storage (000s).

TABLE 11
Inventory regressions[1,2] for the model
log (total inventory/sales) = $á_0$ log(K) + $á_1$ IT%

	11.1	11.2	11.3	11.4
Years:	1977-1987	1986-1993	1977-1987	1986-1993
Fixed effects for:	Industry	Industry	Firm	Firm
ln(*K*)	0.071[a]	-0.067[a]	0.105[a]	0.140[a]
IT% (=*K1/K*)	-1.968[a]	-1.303	-1.134[c]	-2.023[b]
N	10,217	1,324	10,217	1,324
R^2	0.50	0.51	0.88	0.90

[1] The computations are based on Census and Computer Intelligence Data for 1977-1993. All regressions include fixed year effects. Industry effects are 3-digit SIC codes for 1977-1987 and 4-digit for 1986-1993. [a] denotes significant at 1% level, [b] denotes significant at 5% level, [c] denotes significant at 10% level.
[2] *K* is Plant, Property and Equipment (*PPE*), K_1 is computer assets; and IT% is the share of computers in total capital.

market research firm, Computer Intelligence.

The Census Bureau data cover the years 1977, 1982 and 1987, while the Computer Intelligence data cover the years 1986, 1991 and 1993. The former source offers relatively rich information about the composition of employment, and data on computer investment (but not assets); the latter source includes only total employment, but rich data on the composition of computer assets. After linking the Census data for 1987 and the Computer Intelligence data for 1986, we estimated the relationship between computer investment and the level of computer assets, and used this to estimate the value of computer assets in the rest of the Census sample.

We then estimated production functions for both the Census and Computer Intelligence data with both fixed industry and firm effects. While shifting to fixed firm effects significantly reduces the magnitude of the elasticity of computer capital, we still observe excess returns to computers. The reduction in the estimated elasticity is consistent with the interpretation that computer assets are positively correlated with unobserved firm-specific features that contribute to productivity growth. These results are robust across both data sub-samples. Moreover, because the magnitude of the parameter estimates was not affected by the inclusion of regressors intended to control for differences in labour composition, we do not believe that the reduction in the estimated computer elasticity with firm effects is due to unobserved differences in labour quality.

The Census Bureau data on auxiliary establishments (i.e., support, headquarters and other non-operating business units) allowed us to explore the relationship between firm structure, overhead and computers. We found that computers are complementary with auxiliary establishment employment, but the data appear to be too noisy to enable us to detect significant effects of computerization on the composition of employment within auxiliary establishments (which may, perhaps, be regarded as comprising the '*within-firm* service sector'). Although our firm-level analysis found excess returns to computer investment for both manufacturing and non-manufacturing sub-samples, it also illustrated the difficulties of overcoming data limitations when seeking to investigate the effects of computer investment on service productivity.

The Computer Intelligence data for the latter period allowed us to investigate the relationship between productivity (and other operating characteristics of the firm, *e.g.,* inventory-to-sales ratios) and the *composition* of computer assets. This revealed that productivity is strongly related to the number of *personal computers* used by a firm, and that raw computing power matters less than how computers are used. More PCs means that computers are distributed more widely throughout the firm, and that users are more likely to be on networks that allow them to take advantage of such applications as electronic mail.

Our comparison of Census and Computer Intelligence data demonstrated the superiority of using data on stocks of computer asset values rather than flows of computer investment. Our analysis also indicated that mere *counts* of mainframes and minicomputers do not adequately account for quality differences.

The overall conclusion from this research is that computers do contribute positively to productivity growth, yielding excess returns. These excess returns, however, appear to have peaked in about 1986 or 1987, and appear in both the service and non-service sectors. Further improvements will require analysis of firm-level and business-unit data, especially since a huge share of service-sector activity takes place in service units within non-service sector firms. Computers appear to be changing the way in which firms are organized and operated, allowing firms to become more decentralized and altering employment composition. Although demonstrating that computers yield excess returns serves to cast doubt on the traditional version of the productivity paradox, there are still a number of interesting questions. For example, why is there such variability across firms in the productivity of computers and how computers are used? Or, why is it the case that productivity gains which are clearly realized at the business-unit level (*e.g.*, when computers permit significant headcount reductions) often seem to fail to flow through to the firm's bottom line?

Notes

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1 See for example Bailey and Gordon (1988), Loveman (1990), Morrison and Berndt (1994), Roach (1987), Strassman (1990), or Wolf (1997) for papers that fail to detect a positive contribution of computers to productivity growth.

2 See for example, Brynjolfsson and Hitt (1993), Lichtenberg (1995), or Lehr and Lichtenberg (1997).

3 This is partially consistent with the findings of Morrison and Berndt (1994), who found over-investment in computers up until the 1980s, but increases in the marginal benefit-cost ratio by 1988.

4 Investment in Office Computing and Accounting Equipment (OCA) as a share of total investment in non-residential producer durables, increased from 5.9% to 13.2% in nominal terms from 1977 to 1993. (Source: Bureau of Economic Analysis, Department of Commerce, Table 5.8).

5 The equations are approximate because we are substituting *è*IT%* for ln*(1+è*ÉÔ%)*; the two are quite close as long as *è*ÉÔ%* is small. As subsequent discussion will show, since *IT%* is on the order of 1-2%, è may be quite large and this approximation will still be reasonable.

6 The hypothesis that the marginal product for computers is positive implies that *á* > 0 and *è* > -1.

7 The test for excess returns is much stronger than the test of whether computers are productive. A firm operating on its production frontier ought to employ inputs up to the level where the marginal output from an additional dollar of input is balanced across all inputs. Computers yield ‘excess returns’ if a dollar invested in computers

results in more output than a dollar invested in other types of capital and is consistent with the prediction that profit-maximizing firms ought to be using computers more intensely.

8 Lau and Tokutsu (1992) used long run averages to estimate r=0.07, $ä_1$=0.20, $ä_0$=0.05, $E(p_1)$=-0.15, and $E(p_0)$=0.05. Also, note that P_1 /P_0=1 because we assume that K_1 and K_0 are measured in equivalent units of capital. Taken together, these imply that the ratio of the user cost of capital for computer to other types of capital is 6 = (.07+.20+.15)/(.07+.05-.05). This test is quite strong because it assumes that the combined effect of depreciation and expected price declines for computers is 35% per year. This is higher than the quality-adjusted 30% per year price decline for PCs estimated by Berndt, Griliches, and Rappaport (1993) or the 25% per year decline estimated by Gordon (1989). Also, recent data on the relative lease price-to-purchase price for personal computers versus automobiles (a proxy for other types of machinery and equipment capital) is approximately 3 (i.e., the lease-to-purchase ratio for automobiles is approximately 15% and for computers is approximately 43%) based on advertisements in a recent New York Times. Because K_0 includes structures, the comparable ratio would be somewhat higher.

9 There are reasons to suspect that the estimate of the computer share of total assets may be understated both here and in Oliner and Sichel (1993) because of the failure to adequately account for non-hardware types of computer investments (e.g., software) and because valuations based on current prices may understate the value of embodied technological progress (see further discussion below).

10 For example, suppose that total capital (K) is measured correctly, but that K_1 is 50% too low because it includes only computer hardware, excluding an equal investment in software.

11 Valuing computer inputs in current prices may tend to understate the value of embodied technological progress. For example, in 1985, one could purchase an IBM PC/XT for $5,000 that had roughly the same processing power as an IBM 360/25 that cost $500,000 in 1965. As Timothy Bresnahan pointed out in his review of an earlier draft, perhaps we should be more interested in the $495,000 in embodied technological progress than the $5,000 in computer capital when trying to observe a productivity impact from computers in 1985.

12 The sample of firms in the two surveys are different. The AUX includes data on 30,000-40,000 establishments associated with 12,000-17,000 firms of all sizes, whereas the ES includes data for 7,000-8,000 firms with 500 or more employees. Between 3,000-4,000 firms are in both samples and approximately 40% of these firms are present in all three years. The samples include firms from all non-agricultural sectors.

13 The financial data include income and balance sheet data such as sales, assets, compensation, inventories, and employment. The AUX data are aggregated to the firm level and then matched with the ES data. Initially, we had hoped to be able to estimate within-firm production functions but this did not prove feasible because the AUX data are too noisy.

14 The bulk of the CI data are collected via a site-level survey of information processing establishments. The aggregation of these data to the enterprise level was by CI.

15 In the CI regressions, we rely on Compustat data for an estimate of PPE which is often unavailable. Therefore, while the CI sample includes almost 1000 firms, the matched CI/Compustat sample includes closer to 500 firms. Because PPE is included in the

Census data, we were able to match a larger number of firms for 1986/1987.

16 Because the CI firms are larger and larger firms are relatively more computer intensive, this approach may overstate the level of computer assets in smaller firms in the Census sample for 1982 and 1977.

17 Wolff (1997, table 5) reports investment in Office, Computing and Accounting Equipment (OCA) per employee to be $231.8 over 1977 to 1987 (in 1987 $), which helps confirm that our sample is representative of the overall economy.

18 When ranked by employment size, smaller firms were less likely to report investing in computers. However, the share of all size firms reporting investments in computers increased and the gap narrowed. This may partially reflect a reduction in measurement error over time (which may be more severe for smaller firms), but it is also consistent with the earlier adoption of computers by larger firms. The shares of Census Sample firms reporting positive computer investment are:

	1977	1987
Smallest quartile firms	22%	75%
Largest quartile firms	65%	93%
All firms in sample	38%	82%

19 These changes are computed based on median values. The means are higher, but reflect similar trends. See table 4.

20 This is consistent with the estimates reported by Oliner and Sichel (1995).

21 The 'median growth rate in employees per site' is computed by first calculating the growth rate in employees per site for each firm which is present in both 1993 and 1986 and then taking the median of these growth rates. Also, since virtually every site in the CI data is also listed as a data-processing site, this growth in the number of sites is not merely reflecting the diffusion of computers throughout the organization. Because the quality of the CI data collection effort is likely to have improved over time, it is possible that the growth rate in sites per firm is over-stated (because not all sites may have been included in earlier years).

22 Beginning in the 1990s, there has been a trend towards distributed client/server architectures based on linked local area networks of PCs. During the earlier part of our study covered by the Census data, 'distributed systems' were based on the increased use of remote terminals. In both case, computers were being used in a wider range of activities by a wider range of employee types within the organizations.

23 Additional evidence of the diffusion of computer technology throughout the firm is provided by the CI data on Local Area Networks (LANs). The CI data did not collect data on the number of LANs per firm until 1991. However, even from 1991 to 1993, the median number of LANs per firm increased substantially:

	1991	1992
Median number of LANs per firm	14	20
Share of firms with at least 1 LAN	97%	96%
Median number of employees/LAN	689	527

24 For the Census data, mean computer investment per employee was only 28% higher for the largest firms, which were almost 34 times larger than the smallest firms. We might expect larger firms to use computers more intensively both because they may be likely to face greater coordination problems which computers may help solve and because they are likely to be early adopters. In addition, there may be scale economies in computer system investments, especially with respect to mainframes.

25 This is consistent with early adoption by large firms.

26 Computer usage is positively correlated with education (and not surprisingly, household income): 13% or less of workers with less than a high school education use a computer, while over 69% of those with four or more years of college do. The skills-bias indicated by these statistics becomes more apparent when one considers data on usage by occupation and by industry: 68% of managers and professionals versus 15% of operators and labourers use computers; also, 79% of those in the finance and insurance industries versus 17% in construction use computers (table 2).

27 The price for a domestic PC shipped in 1991 ($2,546) is higher than our estimate ($849) because our regressor is the total of PCs and terminals, and terminals are significantly less expensive than PCs. We use the sum of PCs and terminals because it is less noisy then either the count of PCs or of terminals alone which may include significant measurement error. Also, note that the price for a minicomputer shipped in 1991 ($54,522) is close to our estimated value in 1986 ($66,948), but is significantly higher than the estimate for 1991 ($24,346).This may be because the minicomputer category in the CI data includes workstations and high-end PCs that are less expensive and are excluded from the data on minicomputer shipments.

28 To simplify the notation, we will drop the i and t subscripts.

29 We adjusted the data to a common year base and scaled to account for measurement error across the two samples (e.g., mis-matched total employment or sales). Fortunately, the Census data and the CI/Compustat data matched quite well.

30 To compare the computer coefficients in the two regressions, remember that $(I_1/I) = [(\ddot{a}_1+g_1)/(\ddot{a}+g)](K_1/K)$ where g_1 and g (and $\ddot{a}_1$ and $\ddot{a}$) are the growth rates (and depreciation rates) for computer capital and *PPE*, respectively. In the steady state these growth rates are equal to zero and $(I_1/I)=4(K_1/K)$, using the depreciation rates assumed earlier in footnote 8, *supra*. More generally, if computer capital is growing more rapidly than *PPE*, then the proportionality constant would be correspondingly larger.

31 While this approach may produce reasonable estimates of the computer asset share for 1987 and even 1982, we suspect that our estimates for 1977 may not be accurate. Also, as noted earlier, the CI data may over-sample large firms resulting in an overstatement of the level of computer investment (because larger firms are more computer intensive, although the change with size is relatively small).

32 That is, the null hypothesis of no excess returns is rejected if the ratio of the estimated coefficient on the share of computer capital (*IT%*) to the coefficient on ln*(K)* is significantly greater than 5.

33 Although the regressions with firm fixed effects appear to show decreasing returns to scale, we suspect that this is due to the exacerbation of measurement error in within-firm estimation (i.e., using fixed firm effects).

34 That is, higher sales lead firms to invest in more and newer computers. This would also explain the higher productivity of PCs.

35 They used lagged variables as instruments.

36 The coefficients on ln*(K)* and ln*(L)* are not reported to simplify the table. These coefficients were in the expected ranges (i.e., close to the capital and labour shares of total expenditures).

37 For example, because needed infrastructure was missing (David, 1990) or there was a need to train for computer literacy.

38 The ratio of the coefficient on (L_1/L) to the coefficient on *ln L* ought to be equal to 0.98, because average auxiliary compensation is 1.98 times higher than non-auxiliary compensation. Instead, the ratio is 0.46.

39 According to the 1991 Annual Survey of Manufacturers, the average wage was $38K for workers in the computer and office equipment industry and the average auxiliary wage in our sample was $41K per year, so we can apply the same test as described in footnote 38 *supra*.

40 We included R&D expenditures and R&D employment to partially control for unobserved knowledge capital and found that this did not affect the computer coefficient.

41 It is necessary to revise the assumption underlying the hypothesis test outlined in equation 7 to reflect the higher depreciation rate and price changes for equipment (ä_2=0.083, $E(p2)$=-0.05, assumed). With this change, the appropriate hypothesis test becomes, H_0: $\text{á}_1/\text{á}_2=3 \Leftrightarrow$ no excess returns.

42 The test for excess returns for equation 14 is slightly different because the ratio of marginal products is different:

$$H_0\!: \frac{MP_{K_1}}{MP_{K_0}} = \frac{\text{á}_1 K_0}{\text{á}_0 K_1} = \frac{\text{á}_1}{\text{á}_0}\frac{(1-IT\%)}{IT\%} = \frac{\text{á}_1}{\text{á}_0}\frac{(1-0.02)}{0.02} = \frac{R_1}{R_0} = 6 \Leftrightarrow \frac{\text{á}_1}{\text{á}_0} \qquad (15)$$

$= 0.12 =$ no excess returns

43 Notice that the point estimates on *MIPS* and *DASD* are negative (and insignificant).

44 The regressions with industry effects are less interesting because we might suppose that there are significant cross-industry differences in the nature of inventory management and the role that computers play in affecting inventories.

45 For example, computers may allow the firm to maintain a larger range of products in inventory at the same time and still operate with lower inventory levels for each type of product. The cost impact of these changes is likely to be partially offsetting.

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