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Productivity and ICT: A Review of the Evidence

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Abstract
We survey the micro and macro literature on the impact of Information and Communication Technologies (ICTs) on productivity. The "Solow Paradox" of the absence of an impact of ICT on productivity no longer holds, if it ever did. Both growth accounting and econometric evidence suggest an important role for ICTs in accounting for productivity. In fact, the empirical estimates suggest a much larger impact of ICT on productivity than would be expected from the standard neoclassical model that we focus on. We discuss the various explanations for these results, including the popular notion of complementary organizational capital. Finally, we offer suggestions for where the literature needs to go.

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Introduction

Paul Krugman has remarked that productivity is not everything, but in the long run it is almost everything. This is because the key indicator of material well being, national income per person, is fundamentally determined by the growth of labour productivity. Because of greater productivity, society has the option to enjoy more leisure, pay lower taxes, increase public spending or redistribute wealth without making a large proportion of people worse off.

Given the importance of productivity it is somewhat disturbing that for many years 'we could see computers everywhere but in the productivity statistics'. Nobel Laureate Robert Solow (1987) made this remark in response to the simultaneous apparent widespread adoption of computers and slowdown in US productivity growth from the mid 1970s. Much research effort has been devoted since that time to addressing this 'Solow Paradox' and analysing the impact of information and communication technologies (ICTs) on productivity. Because of this research, the outlook in the early 21st century appears more optimistic than it did from the perspective of the 1980s.

This explosion of research has involved academics, statistical agencies and international bodies. There has been greater collaboration between these sectors, which has enabled progress in the generation and analysis of data. The work of private sector organizations and consultancies has also contributed significantly to the debate. In addition to the intrinsic interest of researchers in this question, the availability of very large longitudinal datasets following the same firms and industries over many years has enabled significant progress in research. These large electronic datasets would have been virtually possible to compile and analyse if the ICT revolution had not occurred.

In this paper, we offer a guided tour to some of the main aspects of ICTs and productivity. Section 2 discusses a neoclassical theoretical framework that has been extensively used (either explicitly or implicitly) by most of the studies we survey. We also consider extensions to these theoretical approaches. In Section 3 we detail some of the econometric issues involved in estimating the productivity of information technology (IT). This requires some consideration of the estimation of production functions, an area where there has been considerable econometric advance in recent years. In Section 4 we discuss issues relating to the data; both ideal and actual. The final two sections discuss the results of the empirical studies covering both growth accounting (Section 5) and econometric approaches (Section 6) at the industry and firm level. The studies are presented in summary in Tables 2, 3 and 4.

Given the size of the task, there are several caveats. Our focus is mainly economic, and thus we largely ignore the contributions of many other social scientists.

Our justification is that we want to focus on the quantitative work where economists have tended to dominate. For this reason, we have not attempted to survey the large case study literature, which has thrown up some interesting insights on the role of organizational factors (for example, the McKinsey Global Institute studies). Furthermore, for reasons of space we present only the basics of the many empirical studies in this area.

Within the class of econometric studies, we focus on the estimation of cross industry production functions. There are several econometric studies of particular types of IT in particular sectors, such as trucking (Baker and Hubbard 2004); emergency medical care (Athey and Stern 2002) and schools (Angrist and Lavy 2002; Machin, McNally, and Silva 2006). These studies represent some of the future directions of the discipline and their scant mention should not be interpreted to be a sign of their small importance.

Somewhat preempting the conclusions of our study we want to highlight the following findings. The macro picture is one of remarkable productivity acceleration in the USA during the 1990s, which would appear to be related (at least in part) to IT. Europe has not achieved similar productivity acceleration, which is likely due to the greater 'organizational capital' in US firms. There is some suggestive recent evidence from micro panel studies supporting this, but more work needs to be done to (a) specify more concretely the type of organizational features that promote successful IT usage, and (b) deal with the inherent endogeneity of IT choices.

Theory

Basic approach

We begin by outlining the basic neoclassical approach, which in addition to being the most common approach in the literature, provides a very useful framework for organizing our thinking.

The basic neo-classical approach begins with a production function (F (.)), which relates output, Y, to inputs. One of these inputs is capital; the components of capital are IT capital (denoted C), and non-IT capital K (which includes, for example, buildings). There are also factors of production such as hours of labour L, and materials M[1]. We also allow different levels of efficiency, A (Hicks neutral technology). Consequently

$$Y = AF(L, K, C, M) \qquad (2.1)$$

To illustrate the issues we will assume that the production function can be written in Cobb-Douglas form (although the results we discuss are suitable for much more general forms of the production function). In natural logarithms the production function can be written as:

$$y = a + \alpha_l l + \alpha_k k + \alpha_c c + \alpha_m m \qquad (2.2)$$

where lower case letters indicate that a variable has been transformed into a natural logarithm (e.g. $y = lnY$). In discrete time, the growth rate of output can be written as:

$$\Delta y = \Delta a + \alpha_l \Delta l + \alpha_k \Delta k + \alpha_c \Delta c + \alpha_m \Delta m \qquad (2.3)$$

where Δa is Total Factor Productivity (TFP) growth and the other terms are the growth rates of the inputs. Usually, we can think of Δ as the first difference transformation (e.g. $\Delta y_t = y_t - y_{t-1}$) but we can also consider longer differences (e.g. the average annual growth rate between 1995 and 2000: $\Delta_5 y = (y_t - y_{t-5})/5$).

Several approaches are now possible. The first approach we consider is called growth accounting, which is popular in the macro literature. The second approach is to estimate some form of the production function directly, an approach popular in the micro literature. However, it should be noted that growth accounting is also possible at the micro level and production function estimation is also possible at the macro level.

Growth accounting

Under the assumption that factor markets and product markets are perfectly competitive their shares in revenue can replace the coefficients on factor inputs. These are strong assumptions, but there are many ways to relax them and allow for degrees of imperfect competition. Denoting a revenue share by *s*, we can write:

$$\alpha_x = s_x = \frac{\rho_x X}{pY} \qquad (2.4)$$

where ρ_x the unit cost of factor *X* and *p* is the output price (so *pY* is revenue). For example, ρ_c will be the Hall-Jorgenson user cost of IT capital. For labour, ρ_l is simply the wage rate. Given this, we can re-write the production relation as:

$$\Delta y = \Delta a + s_l \Delta l + s_k \Delta k + s_c \Delta c + s_m \Delta m \qquad (2.5)$$

Note that, with the exception of TFP growth, Δa all the objects on the right-hand side of this equation are observed. Growth accounting (over a period) divides output growth into the contribution of the (weighted) growth of inputs and the contribution of the residual. Since Solow (1957), the contribution of the residual has generally been found to be a large component of total labour productivity growth. This is sometimes labelled technical change, but obviously it includes everything in the economy that improves (or reduces) the efficiency with which factors are used (as well as some amount of measurement error).[2]

Under constant returns to scale (i.e. $\alpha_l + \alpha_k + \alpha_c + \alpha_m = 1$), we can re-write the growth equation in terms of labour productivity growth:

$$\Delta(y-l) = \Delta a + s_k \Delta(k-l) + s_c \Delta(c-l) + s_m \Delta(m-l) \qquad (2.6)$$

Therefore, output growth per hour is a function of inputs per hour and TFP growth. Clearly the contribution of IT capital will be $s_c \Delta(c-l)$. If the production function is Leontief in materials, we can write the relationship in value added (v) terms as

$$\Delta(v-l) = \Delta a + s_k \Delta(k-l) + s_c \Delta(c-l) \qquad (2.7)$$

This provides a basic picture of growth accounting. In the IT literature growth accounting has focused, naturally enough, on the importance of the IT contribution by decomposing the equations by industry because IT contributes to aggregate productivity growth in two distinct ways. First, through IT-capital deepening, $s_c \Delta(c-l)$ as sectors increase the intensity of their IT use. Second, through TFP growth in IT producing sectors.

There are several well-known problems with growth accounting. First, it describes, but does not explain. There is no attempt to claim that there is any causal connection between changes in inputs, such as ICT, and productivity. Secondly, the assumptions underlying growth accounting are strong and generally not tested (for example, perfect competition). It is simply assumed in growth accounting that the share of ICT capital measures its contribution, and no attempt is actually made to estimate the strength of the relationship in the data. Thirdly, if there are externalities related to factors they will be included in the residual, and the contribution of these factors will be underestimated. Modern endogenous growth theorists emphasize that there may be important knowledge spillovers from human capital, especially the highly skilled workers employed in the research and development (R&D) sector (see, for example, Aghion and Howitt 1998). Consequently, traditional growth accounting will systematically underestimate the importance of these factors in accounting for economic growth (see Sianesi and Van Reenen (2003) for a survey of the role of human capital in growth). Finally, the model is one of static long-run equilibrium and takes no account of adjustment costs.

Some extensions to the basic model

Complementary organizational capital and IT

There has been considerable discussion in the literature that the measured ICT may be only the tip of the iceberg. Successful implementation of an ICT project requires reorganization of the firm around the new technology.[3] Reorganization incurs costs, whether in the shape of fees paid to consultants, management time, or expenditure on the retraining of workers. There is much anecdotal evidence supporting this view, and it has been claimed that the total cost of an ICT project can be four or more times the amount paid for the equipment and software. Yang and Brynjolffson (2001, Table 2) cite evidence that the total start-up cost (that is, the costs incurred within the first year) of an Enterprise Resource Planning (ERP) suite is five times the cost of the hardware and software licences. Based on econometric evidence of the effect on stock prices of ICT investment, Brynjolffson, Hitt, and Yang (2002) suggest that as much as $9 of total investment is associated with $1 of ICT investment. This additional expenditure could be interpreted simply as adjustment costs, which are perhaps particularly high in the case of ICT. These adjustment costs can be estimated econometrically.

More generally, a production function can be estimated, where there are interactions between organizational capital, *O*, and ICT capital (the previous discussion was in terms of perfect complementarity - a firm has to spend $9 extra on organization when it buys IT). One form of the production function could be (cf. Bresnahan, Brynjolfsson, and Hitt 2002)

$$y = a + \alpha_l l + \alpha_k k + \alpha_c c + \alpha_m m + \alpha_o o + \alpha_{oc}(c * o) \qquad (2.8)$$

where the hypothesis is $\alpha_{oc} > 0$[4]. Note that this is different from the situation where the firm may simply have more organizational capital in general, and this is positively correlated with ICT capital (α_{oc} =0, but cov(*C,O*)>0). In this case, the importance of ICT capital will be overestimated if organizational capital is not properly measured.

In another scenario, *O* is essentially fixed and exogenous to the firm. For example, entrepreneurs establish firms that have a distinctive managerial culture, which it is extremely difficult to change unless the firm (or plant) closes down or is taken over (for models of this type see Syverson 2004). A differenced version of this equation would be

$$\Delta y = \Delta a + \alpha_l \Delta l + \alpha_k \Delta k + \alpha_c \Delta c + \alpha_m \Delta m + \alpha_{oc}(o * \Delta c) \qquad (2.9)$$

There will be systematic variation in the ICT coefficient depending on whether firms have a high or low value of *O*. For example, if US multinationals have systematically greater organizational capital than non-US multinationals this implies a positive estimate of the interaction between ICT capital and a dummy for whether the firm was a US multinational (see Bloom, Sadun, and Van Reenen 2005 for evidence in favour of this hypothesis).

Skills

There is much evidence to show that technology and skills are complementary (for example, Chennells and Van Reenen 2002, Machin and Van Reenen 1998). Failure to account for skills in equation (2.2) could also bias upwards the estimated effects of IT, just as would the omission of organizational capital. Caroli and Van Reenen (2001) examine an extended version of the production function allowing for interactions between IT, organizational capital, and skills. They find that the complementarity between IT and organization is not significant when organization, skills, and the interaction between them are controlled for.

General purpose technologies and spillovers

It is frequently argued that ICT is a 'general-purpose' technology (GPT). This has several implications; first, adoption of a GPT entails experimentation that may lead to innovation by the adopting firms, which in turns shows up as TFP growth. Second, as well as innovating themselves, firms can learn from the (successful or unsuccessful) innovation efforts of others, so there are spillover effects (Bresnahan and Trajtenberg 1995). Thirdly, there may be network effects specific to the widespread use of ICT: ICT may be more effective when many firms in a region or industry are using similar levels or types of ICT.

These considerations cause researchers to look for spillovers from ICT in the same way that researchers looked for R&D spillovers. [5] The method generally employed is to augment the production function with a spillover term (denote this SPILL), which is the ICT of some of the other firms in the economy.

$$y = a + \alpha_l l + \alpha_k k + \alpha_c c + \mu SPILL + \alpha_m m \qquad (2.10)$$

We are interested in whether $\mu > 0$.

The main problem here is how to construct the SPILL measure. In general, this requires the specification of weights or 'distances' (d_{ij}) between firms *i* and *j*. So in general

$SPILL_i = \sum_{j,i \neq j} d_{ij} C_j$. The distances could be based on industry – for example, all the other firms in my industry are given a weight of unity (d_{ij} =1), while firms outside firm i's industry are weighted zero (d_{ij} =0). If spillovers come from forward or backward linkages, input-output matrices or trade matrices could be used. Alternatively, weighting can be based on geography or technology class.

It should be emphasized however, that IT, unlike R&D, is embodied, therefore knowledge spillovers will be less likely. Network effects may be more important, but these might apply to specific forms of ICT (like operating systems or communication networks) rather than ICT in general.

Econometric models

There are many problems involved in estimating the production function for ICT. Some of these are generic issues related to the estimation of production functions. For instance, unobserved heterogeneity: there are many factors correlated with productivity that we do not measure. If unobserved heterogeneity is constant over time then panel data can help. The unobserved factor can be treated as a fixed effect and then the estimation can proceed with either dummy variables for each firm (that is, the within groups estimator) being included, or by differencing the data (for example, first differences). Another problem is endogeneity. The factor inputs (such as IT) are chosen by firms and are not, therefore, exogenous when included on the right-hand side of the production function. One solution to this is to find external instruments that affect the decision to invest in IT, but do not affect the productivity of the firm directly.[6]

The literature has not followed up this solution, however, and most studies ignore these issues and simply estimate a production function using ordinary least square (OLS) methods. However, some studies examine various approaches for dealing with these problems and a minority[7] actually compare the results derived from alternative advanced econometric techniques. Below we discuss three approaches: TFP-based, General Method of Moment (GMM), and Olley Pakes (OP).

TFP-based approaches

A common approach in the ICT literature dealing with this issue is to consider a transformation that constructs a measured TFP growth term. For example, Brynjolfson and Hitt (2003) estimate the following forms of equations:

$$\Delta \tilde{a} = \beta_1 \Delta c \qquad (3.1)$$

where the dependent variable is measured TFP (or 'four factor' TFP')

$$\Delta \tilde{a} = \Delta y - s_l \Delta l - s_k \Delta k - s_c \Delta c - s_m \Delta m \qquad (3.2)$$

If ICT earned 'normal returns' then the estimated coefficient in equation (3.1) would equal zero (β_1 =0). Unfortunately, although this resolves the endogeneity problem for the non-ICT factor inputs by moving them from the right-hand side to the left-hand side of the equation, the endogeneity of ICT remains a problem. In fact, it is likely to be exacerbated as the construction of measured TFP involves the variable of interest on the right-hand side of the equation. Any measurement error in ICT will be transmitted into a biased coefficient on β_1[8].

An additional problem is that classical measurement errors in ICT will generate an attenuation bias towards zero for β_1. This is one reason for turning to longer differenced models, the approach adopted by Brynjolffson and Hitt (2003) (although they interpret their increasing coefficients as being due to unmeasured organizational capital rather than measurement error). In general, the attenuation bias should be less for longer differences than for shorter differences as the transitory shocks will be averaged out increasing the signal to noise ratio for the ICT measure (Griliches and Hausman 1986). Unfortunately, in econometrics as in life there is no free lunch. Although long-differencing the data reduces the random measurement error, endogeneity problems are exacerbated because the transformed error term now includes more time periods.

General method of moment (GMM) approaches

For notational simplicity, re-consider the basic production function as

$$y_{it} = \theta x_{it} + u_{it} \qquad (3.3)$$

where θ is the parameter of interest on a single factor input, x. Assume that the error term, u_{it}, takes the form

$$u_{it} = \eta_i + \tau_t + \omega_{it}$$
$$\omega_{it} = \rho\omega_{it-1} + \upsilon_{it} \qquad (3.4)$$

τ_t represents macro-economic shocks captured by a series of time dummies, η_i is a correlated individual effect, and υ_{it} is a serially uncorrelated mean zero error term. The other element of the error term, ω_{it} is allowed to have an AR(1) component (with coefficient ρ), which could be the result of measurement error or slowly evolving technological change. Substituting (3.4) into (3.3) gives the dynamic equation:

$$y_{it} = \pi_1 y_{it-1} + \pi_2 x_{it} + \pi_3 x_{it-1} + \eta^*{}_i + \tau^*{}_t + \upsilon_{it} \qquad (3.5)$$

The common factor restriction (COMFAC) is $\pi_1\pi_2 = -\pi_3$. Note that $\tau^*{}_t = \tau_t - \rho\tau_{t-1}$ and η_i*= (1- ρ)η_i.

Blundell and Bond (2000) recommend a system GMM approach to estimate the production function and impose the COMFAC restrictions by minimum distance. If we allow inputs to be endogenous, we will require instrumental variables. We consider moment conditions that will enable us to construct a GMM estimator for equation (3.5). A common method is to take first differences of (3.5) to sweep out the fixed effects:

$$\Delta y_{it} = \pi_1 \Delta y_{it-1} + \pi_2 \Delta x_{it} + \pi_3 \Delta x_{it-1} + \Delta\tau_t^* + \Delta\upsilon_{it} \qquad (3.6)$$

Since υ_{it} is serially uncorrelated the moment condition:

$$E(x_{it-2}\Delta\upsilon_{it}) = 0 \quad (3.7)$$

ensures that instruments dated t-2 and earlier[9] are valid and can be used to construct a GMM estimator for equation (3.6) in first differences (Arellano and Bond 1991). A problem with this estimator is that variables with a high degree of persistence over time (such as capital) will have very low correlations between their first difference (Δx_{it}) and the lagged levels being used an instrument (for example, x_{it-2}). This problem of weak instruments can lead to substantial bias in finite samples. Blundell and Bond (1998) point out that under a restriction on the initial conditions another set of moment conditions is available:[10]

$$E(\Delta x_{it-1}(\eta_i + \upsilon_{it})) = 0 \quad (3.8)$$

This implies that lags of first differences of the endogenous variables can be used to control for the levels in equation (3.5) directly. The econometric strategy is to combine the instruments implied by the moment conditions (3.7) and (3.8). We can obtain consistent estimates of the coefficients and use these to recover the underlying structural parameters.

The Olley-Pakes method

Reconsider the basic production function[11] as:

$$y_{it} = \alpha_l l_{it} + \alpha_m m_{it} + \alpha_k k_{it} + \alpha_c c_{it} + \omega_{it} + \eta_{it} \quad (3.9)$$

The efficiency term, ω_{it} is the unobserved productivity state that will be correlated with both output and the variable input decision, and η_{it} is an independent and identically distributed error term. Assume that both capital stocks are predetermined and current investment (which will react to productivity shocks) takes one period before it becomes productive, that is, $K_{it} = I^K_{t-1} + (1-\delta^K)K_{it-1}$ and $C_{it} = I^C_{t-1} + (1-\delta^C)C_{it-1}$.

It can be shown that under certain regulatory conditions the investment policy functions for ICT and non-ICT are monotonic in non-ICT capital, ICT capital, and the unobserved productivity state.

$$i^K_{it} = i^K_t(k_{it}, c_{it}, \omega_{it}) \tag{3.10}$$

$$i^C_{it} = i^C_t(k_{it}, c_{it}, \omega_{it}) \tag{3.11}$$

The investment policy rule, therefore, can be inverted to express ω_{it} as a function of investment and capital. Focusing on the non-IT investment policy function it can be inverted to obtain the proxy: $\omega^K_t(i^K_{it}, k_{it}, c_{it})$. The first stage of the OP algorithm uses this invertibility result to re-express the production function as:

$$\begin{aligned} y_{it} &= \alpha_l l_{it} + \alpha_m m_{it} + \alpha_k k_{it} + \alpha_c c_{it} + \omega^K_t(i^K_{it}, k_{it}, c_{it}) + \eta_{it} \\ &= \alpha_l l_{it} + \alpha_m m_{it} + \phi(i^K_{it}, k_{it}, c_{it}) + \eta_{it} \end{aligned} \tag{3.12}$$

where $\phi(i^K_{it}, k_{it}, c_{it}) = \phi_t = \omega^K_t(i^K_{it}, k_{it}, c_{it}) + \alpha_k k_{it} + \alpha_c c_{it}$

We can approximate this function with a series estimator or non-parametric approximation and use this first stage results to get estimates of the coefficients on the variable inputs. The second stage of the OP algorithm is:

$$y_{it}^* = y_{it} - \alpha_l l_{it} - \alpha_m m_{it} = \alpha_k k_{it} + \alpha_c c_{it} + \omega_{it} + \eta_{it} \qquad (3.13)$$

Note that the expectation of productivity, conditional on the previous period's information set (denoted Ω_{t-1}) is:

$$\omega_{it} |_{\chi_{it}=1} = E[\omega_{it} | \omega_{it-1}, \chi_{it} = 1] + \xi_{it} \qquad (3.14)$$

where $\chi_{it} = 1$ indicates that the firm has chosen not to shut down (a selection stage over the decision to exit can be incorporated in a straightforward manner). This expression for productivity state is based on the assumption that unobserved productivity evolves as a first order Markov process. Again, we assume that we can approximate this relationship with a high order series approximation $g\,(\omega_{it-1})$. Substituting this in to the second stage, and making expectations conditional on the previous period's information set gives:

$$E(y_{it}^* | \Omega_{t-1}) = \alpha_k k_{it} + \alpha_c c_{it} + g[\phi(i_{it-1}^K, k_{it-1}, \alpha_c c_{it-1}) - \alpha_k k_{it} - \alpha_c c_{it}] \qquad (3.15)$$

Since we already have estimates of the ϕ_{t-1} function this amounts to estimating by Non-Linear Least Squares (NLLS). We now have all the relevant parameters of the production function.[12]

Data issues: Measuring ICT

Ideal measures of capital in a production function context

The ideal measure capturing the economic contribution of capital inputs in a production theory context is *flow of capital services*. Building this variable from raw data entails non-trivial assumptions regarding: the measurement of the investment flows in the different assets and the aggregation over vintages of a given type of asset.[13] Assuming for the moment that we can measure investments in the specific asset without error,[14] we investigate the latter point.

For the sake of simplicity, we assume a framework in which only one type of capital is used for production. Output will depend on the aggregation of the different vintages of investments made over the years, after allowing for the fact that the capacity of earlier investments decays after installation. Defining the decay factor for an investment of *s* years old d_s, and I_{t-s} as the real gross investment of vintage *s*, the aggregate capital stock can be written as:

$$K_t = \sum_{s=0}^{n} (1 - d_s) I_{t-s} \qquad (4.1)$$

If we assume that the rate of decay is constant over time (geometric rate of decay), then Equation 1 takes the very simple form:

$$K_t = I_t + (1-d)K_{t-1} \tag{4.2}$$

In the case of geometric decay, the rate of decay is equal to the *depreciation rate* (δ) (Oulton and Srinivasan 2003). Depreciation measures the difference between the price of a new and a one-year old asset at time *t*. Defining the price of a specific asset of age *j* at time *s* as $p_{s,j}$, then the depreciation rate is:

$$\delta_t = \frac{(p_{t,j} - p_{t,j+1})}{p_{t,j}} \tag{4.3}$$

Assuming that the depreciation rate of the asset does not vary over time we can omit the time subscript. A concept related to depreciation rate is the capital gain/loss (f) associated with the investment in the specific asset. The capital gain/loss is defined as the change in the price of a new asset between periods *t-1* and *t*, that is:

$$f_{t,j} = (p_{t,j} - p_{t-1,j}). \tag{4.4}$$

Both depreciation and capital gain/loss affect the definition of the *rental price* $(\rho_{t,j})$ for the capital services of a capital input of age *j* at time *t*. This is defined as:

$$\rho_{t,j} = r_t \cdot p_{t-1,j} + \delta \cdot p_{t,j} - f_{t,j} \tag{4.5}$$

where r_t is the actual nominal rate of return during period *t*. The rental price is what the company would pay if instead of buying the capital good, it rents it from another firm. A profit-maximizing firm will hire the capital good up to the point when the rental price equals the marginal revenue of the product of the capital good. Under perfect competition, the rental price will be equal to the value of the marginal product of the asset. In this case, the asset is said to deliver normal returns. When the marginal product is higher than the rental price, then the asset is said to deliver excessive returns.[15]

Basic capital theory applies equally to both ICT and non-IT assets. As this brief description suggests, empirical implementation of the theory of capital measurement is far from simple. This seems to be particularly true for ICT assets, as they entail several problematic issues related to the measurement of investment flows, and of depreciation rates and price deflators. In the next two sections we explore how the research has dealt with these issues, focusing first on industry level data, and then looking at firm level studies.

Measurement of ICT capital at the industry level

This section describes the main sources and methodologies used to measure ICT assets in an industry level framework, with a specific focus on the methodologies developed within the main US statistical offices – the Bureau of Economic Analysis (BEA) and the Bureau of Labor Statistics (BLS). The BEA and BLS are the major data sources for studies that apply industry data to examine the productivity impact of ICT in the US economy. Moreover, US methodologies represent the frontier for ICT capital measurement and have been widely applied in non-US contexts[16] to derive industry level measures of ICT capital.

US data

Both the BEA and the BLS develop data on capital stocks, by asset and industry, applying the Perpetual Inventory Method (PIM) to real investment figures. The BEA publishes basic industry level data on ICT spending for the US economy.[17] These estimates are derived using a top down approach. First, gross investments in ICT for the total US economy are computed starting from micro data - produced monthly by the Census Bureau – on computer shipments. Exports, intermediate, households, and government purchases[18] are deducted from this total, and imports are added. Second, industry totals on overall investments are built from micro data on establishments from the Economic Census and the Annual Capital Expenditures Survey (ACES) (since 1992) or the Plant and Equipment Survey (before 1992). To obtain series of ICT (and non-IT investments) by industry, the industry and asset totals are combined and distributed across the different industries using an occupational-employment-by industry matrix developed by the BLS, as documented in Bond and Aylor (2000), (implicitly) assuming a labour-capital fixed coefficient technology. BEA publishes the estimated asset-by-industry flows of all assets in the Capital Flows Table (CFT) and the Fixed Reproducible Tangible Wealth Investment Matrix (FRTW).[19]

Measuring nominal ICT flows is the first of a series of adjustments needed to obtain proper ICT capital. A basic step is the creation of appropriate deflators - to convert nominal flows into real flows. This issue is of particular relevance for ICT assets, which have experienced dramatic price and quality changes over the years. The BEA and the BLS, in concert with academic and computer industry economists, have made significant improvements in developing quality-adjusted prices for computer equipment.[20] Since the early 1990s, the deflators used by BEA for computers and peripheral equipment have been derived from the producer price index (PPI) and the import price index, quality adjusted by BLS using hedonic techniques (briefly described in Holdway 2001).[21]

Another component is the creation of appropriate depreciation schemes – to take account of the rate of decay of the different vintages of investments. BEA's depreciation schemes differ from those used by the BLS. Since 1997, the BEA has used age-price depreciation for its weights, the assumption being that the depreciation pattern of most assets declines geometrically over time.[22] In contrast, the BLS uses a hyperbolic age-efficiency function.[23]

European Data

European statistics offices' published industry data on ICT assets lag behind the US. They have produced various country specific industry level data sets on ICT investment flows.[24] The dataset developed by van Ark, Inklaar and McGuckin (2002) is an example of combining official statistics on ICT flows at industry level for EU economies with US methodologies (especially on depreciation patters and hedonic prices), to produce broadly comparable estimates of ICT stocks from the late 1970s to 2003.[25] In order to build series for real ICT investments, they applied country specific data deflators obtained through the price index harmonization method developed by Schreyer (2002), using US deflators adjusted for each country's general inflation. Once the flows are obtained, capital stocks are derived applying PIM to US depreciation rates taken from Jorgenson and Stiroh (2000).

Discussion

Despite the major effort made by US statistical offices in the context of ICT measurement, and especially the development of robust ICT deflators based on hedonic techniques, the construction of the asset-by-industry investment matrix from which capital stocks are derived seems to suffer from potentially problematic measurement issues[26] (Becker *et al.* 2005). Similarly, available European data rely on interpolation techniques, as, for most European countries, the investment series are available only for specific years.[27]

Crepon and Heckel (2002) give examples of some of the problems that can arise when using industry level estimates of ICT stocks developed in a national accounting framework. In their work, measures of ICT capital at the two-digit level are built using firm level data on ICT assets declared by firms in their tax returns. The industry data are built for an average of 300,000 firms per year over the period 1984-1998, and compared to the figures reported by Cette, Mairesse, and Kocoglu (2000) based on National Accounts. The share of ICT capital in value added, obtained through the aggregation of firm level data, is 1.7 per cent, while the share derived from National Account sources is 0.5 per cent. This stark difference may be due to the more detailed data entries obtained from micro sources, but also could be due to the different assumptions related to the PIM employed in the National Accounts' estimations.[28]

Measures of ICT capital at firm level

Using micro data rather than industry data allows the well-documented firm level heterogeneity in productivity and investment patterns to be taken into account, which is particularly relevant in the context of ICT assets. ICT frequently is found to have a differential impact on firm level productivity according to characteristics such as organizational structures and skills that are likely to differ even across firms within the same industry.

Micro context, private surveys

The first attempts to estimate the role of IT assets on firm level productivity data were made by Brynjolfsson and Hitt (1995, 2003). The data they used typically refer to volume measures of firms' hardware stocks on site, collected through telephone surveys organized and managed by private organizations such as the Computer Intelligence Intercorp (CII). These volume measures are translated into value measures of hardware stocks using price and computing capacity information provided by CII.[29]

There are two advantages of such data. First, the detailed information collected (hardware stocks by type of equipment) provides a very precise snapshot of the type of IT stocks existing at a specific site, and does not require PIM. Secondly, as many of the firms in these surveys were sampled in different years, the data are suitable for longitudinal productivity analysis.

However, there are also some problematic aspects to their use. First, for the purposes of productivity analysis the IT data – collected at site level – needs to be matched with data from other financial information sources (such as Compustat for the US or Amadeus for several European countries), which refer to firms rather than sites within a firm. This implies that the IT data need to be adjusted by aggregation if multiple sites belonging to a single firm are sampled, or by applying weighting schemes to project the site level information to firm level. Secondly, as these type of IT surveys target very large firms (for the US the sample is Fortune 1000 firms), there might be a selection issue biasing the productivity results.

Micro context, census based data

In the last decade statistical offices have played a major role in collecting IT information at firm level. These data now represent a valid alternative to the micro level IT measures collected by private organizations, and are typically matched to other census based information on output and inputs, or to publicly available databases (such as Compustat), which contain firm level financial information.

In most cases, statistical offices collect information related to the *use* of IT equipment, rather than precise measures of IT expenditure or IT stocks. The surveys are at the employee level (that is, an employee of a specific firm is surveyed about his/her own particular use of IT), as in Greenan and Mairesse (1996),[30] or at firm level (that is a representative of the firm is asked about the number of employees using IT in general, about a specific type of IT equipment or procedure, such as broadband or e-commerce), as in Maliranta and Rouvinen (2004).[31] Using a similar approach, Atrostic and Nguyen

(2005) for the US, and Atrostic *et al.* (2004) for Japan, employ firm level information on IT infrastructures (a dummy variable taking value one if the firm uses computer networks) to explore how firms use IT,[32] rather than how much they spend on it.

More recently, statistical offices have begun to collect micro level information on investment expenditures in IT. This type of information has the clear benefit of providing a direct measure of investment that can be quite easily used in a production function context. However, the IT investment data typically have been collected on a cross sectional basis, requiring the use of different approximations to recover measures of productive stocks of IT equipment for use in a production function context from flows.[33]

The existence of detailed information on IT flows over consecutive time periods allows researchers to build measures of IT stocks more closely following the procedure established in the PIM (see Bloom, Sadun, and Van Reenen 2005; Hempell 2005).[34] However, estimating capital stocks using PIM implies specific assumptions regarding the starting point of the PIM recursion.[35] This introduces a degree of measurement error in the estimates of stocks, especially when the time series is short. This problem is partially offset for IT assets, as they typically have a very high depreciation rate (≈30 per cent).

Discussion

Compared to IT data collected by private organizations, the census based data yield larger and more representative samples. Moreover, although the IT measures and the data collection criteria were generally determined independently by each country, recently there has been some multi-national collaboration (such as the OECD International Micro Data Initiative), which it is to be hoped will facilitate cross country comparisons of IT studies. The main issues in the use of these data are the scant availability of time series information (for both categorical variables and expenditure information) and the problems related to software measurement.

Conclusions on data

Despite recent improvements, the gap between the theoretical conception of IT capital services and empirical measures of IT assets is still wide. This applies to industry level data where the estimation of the IT stocks may be undermined by problems related to the imprecise allocation of flows across different industries (US) and to the use of heavy interpolation techniques (Europe). The problem also applies to firm level data where information about investments is often not available, and if it is, it often covers a very short (or no) time series. In fact, many of the studies discussed below rely on even cruder indicator variables whose connection with the theory is likely to be even looser. Software continues to be a major problem as, below the macro level, it is rarely measured directly.

Results from growth accounting exercises

In our view, four stylized facts, which are discussed below, emerge from the macro growth accounting literature:

1. The Solow Paradox arose because ICT was a small part of the capital stock;

2. Productivity growth has accelerated in the US since 1995;
3. This acceleration appears to be linked to ICT;
4. There has been no acceleration of productivity growth in the EU, mainly due to the performance of the ICT using sectors.

The macro studies are described in Table 2. All our summary tables take the same form. Column 1 lists the authors; column 2 the countries and levels of aggregation; column 3 presents the data; and column 4 the measure of ICT used. Columns 5 and 6 respectively present the methods and results.

Some of the earliest studies aimed at understanding the Solow Paradox: that computers were visible everywhere except in the productivity statistics (Solow 1985). Oliner and Sichel (1994) used a growth accounting framework and careful analysis of BEA and BLS data to show that this paradox was more apparent than real. Computers could not make a large contribution to aggregate productivity growth in the 1970s and 1980s because they constituted a very small proportion of aggregate US capital stock (about 2 per cent in 1993). Since then the importance of ICT has grown considerably. Basu *et al.* (2003) estimate that the share of ICT in US value added in 2000 in the private non-farm economy was 5.5 per cent (1.6 per cent computer, 2.31 per cent software and 1.59 per cent communication). Although it remains a relatively small share of total value added, ICT makes a substantial contribution to productivity growth because of its fast growth rate and high rate of depreciation (giving its larger revenue share).

One of the most remarkable facts has been the rapid growth of labour productivity in the US economy since 1995 (see Figure 1). This has continued despite the high tech crash and the 9/11 terrorist attacks, and reversed a period of slow US productivity growth that set in after the Oil Shocks of the mid-1970s. Many authors point to IT as having an important role in this acceleration.

Notice that the acceleration of productivity growth is a double difference (where the Δ is annual averages over many years):

$$\Delta\Delta(y-l) = \Delta\Delta a + s_k \Delta\Delta(k-l) + s_c \Delta\Delta(c-l) + s_m \Delta\Delta(m-l) \qquad (5.1)$$

An example of a growth accounting exercise is given in Table 1 (Jorgensen and Stiroh 2000). The authors examine the sources of output growth in the 1974-90 period and the 1995-99 periods (the 1990-95 period covered a deep recession and therefore was not included; however, its inclusion does not have much effect). Looking first at column (1) output growth in the early period was 3.13 percentage points per annum. The contribution of ICT was relatively small – about 0.37 percentage points per year or about 10 per cent (=.37/3.13) of the total. In the later period, the contribution made by ICT is more prominent. Output growth rose to 4.76 percent per year, 20 per cent (1.01 per cent) of which was due to ICT. Furthermore, there was a significant increase in TFP growth from a third of a percent per year to just less than 1 per cent per year. Some of this TFP growth was concentrated in the ICT producing sectors (semi-conductors, computers, etc.).

Oliner and Sichel (2000, 2002) corroborate Jorgensen's results that IT made an important contribution to US productivity acceleration. By splitting the economy into IT producing and using sectors they found that there were important contributions made by IT in both sectors.

What drives these IT lead increases in productivity? In the growth accounting framework the model is relatively simple: there has been rapid technological progress in the IT producing sectors. In particular, the technology cycle for semi-conductors appears to have speeded up after 1994 and this led to a very rapid fall in quality-adjusted prices for IT goods (Jorgenson 2001). This was reflected in TFP growth in the IT producing sectors and IT capital deepening in other sectors (that is, since the user cost of IT capital had fallen there was substitution into IT capital and away from other factors of production). Both elements contributed to productivity growth, but the underlying factor is rapidly falling IT prices.

In a provocative series of articles, Gordon (2000, 2003) takes issue with the view that ICT use played an important role in US productivity growth post 1995. He is skeptical about the ability ICT to affect productivity growth and in Gordon (2000), he claims that outside the IT producing sector, productivity growth in the US economy was entirely cyclical. Despite the inherent problems of knowing exactly how to correct for the cycle, this view had some plausibility in the late 1990s. It seems very implausible at the end of 2005. The US economy has suffered some cyclical downturns with the stock market crash of 2000, 9/11, the Iraq War, high oil prices, etc. but productivity growth has continued to power ahead.

Furthermore, Stiroh (2002a) produced econometric evidence based on industry data that there was significant productivity growth in the intensive IT using sectors, even after controlling for macro-economic shocks.

Figure 1 also shows productivity growth in Europe. European productivity growth over the whole period since the Second World War has outstripped US productivity growth, generating a convergence in productivity levels. Since 1995, however, European productivity growth has shown no acceleration.

This is also illustrated in Figure 2, which depicts a more straightforward comparison of productivity growth between sectors when we divide the economy into ICT producing sectors, ICT using sectors (those that use ICT extensively, for example, retail, wholesale, and finance), and the rest of the economy (excluding public administration, health, and education). The bars show the acceleration of productivity. In the US economy, illustrated on the left hand-side of the diagram we can see the acceleration in productivity growth, and that this acceleration was strongest in the ICT using sectors (up from 1.2 per cent per annum in the early 1990s to 4.7 per cent per annum after 1995). There is also a smaller acceleration in the ICT producing sectors (up by 1.9 percentage points). Outside these sectors, there was a deceleration in productivity of about half a percentage point. The right hand side of the diagram shows the picture for the European Union (the 15 members pre-2004). Again, there is productivity acceleration in the European ICT producing sectors, and a deceleration in the non-ICT sectors, but unlike the USA, no acceleration of productivity in the ICT using sectors. This is somewhat surprising when the price of ICT is similar throughout the world.

There has been much discussion over this productivity difference between the US and Europe, but no consensus has emerged. Some authors claim it is simply a matter of time before Europe resumes the catching up process (Blanchard 2004) while others point to more long-term structural problems in Europe such as over-regulated labour and product markets (Gust and Marquez 2004). Basu *et al.* (2003) examine the differences between the US and UK - unlike the US but like other European countries, the UK did *not* experience a productivity acceleration 1995-2000 relative to 1990-1995.[36] They found the US-UK difference difficult to account for, but argued that the UK is likely to catch up because of its later investment in complementary organizational capital.

Econometric results for IT and productivity

Industry level

Early industry studies (for example, Berndt and Morrison 1995) found no significant relationship between IT and productivity. Industry level studies using more recent data, found significant returns to IT capital over the 1987-2000 period, based on a study of 58 industries (Stiroh 2004). Stiroh's study looked at IT capital as a whole, and at the individual sub-components (computers and telecom). Although Stiroh (2002a) found there was faster productivity growth in the IT intensive sectors post 1995, Stiroh (2004) found no evidence that the coefficients on IT capital rose in 1996-2000 (compared to 1987-1995). The absence of effects from earlier studies may be due less to the time period and more to the combination of noisier data and IT being a much smaller proportion of total capital.

However, when Stiroh (2004) looks at econometric estimators that attempt to control for fixed effects (for example, through differencing the data) and/or endogeneity (for example, through GMM) there are few significant results. This may be due to genuine misspecification and the absence of an IT effect or, more plausibly, because the industry data are too coarse for some of the more sophisticated econometric approaches.

Most of the other studies in the industry level literature focus on TFP growth equations of the type discussed above in the TFP approaches section. Overall, the results mirror Stiroh's findings. The IT coefficients tend to be generally insignificant, unstable across time, and across countries (for example, Basu *et al.* 2003, Table 8). The TFP regressions have the problems of the aggregate industry data and the problems discussed in the section on TFP approaches, that IT is included on the left hand-side and the right hand-side of the estimating equations.

Given concerns about aggregation and other biases attention has shifted to the more micro-level.

Firm level

What do we know?

The results at firm level (or below) are summarized in Table 4. There are some prominent features.

First, most studies do reveal a positive and significant association of IT with productivity. This is reassuring as many were undertaken in response to the Solow paradox, which suggested there was no productivity impact from IT.

Second, the magnitude of the IT coefficients is larger than might be expected from the standard neoclassical assumptions underlying the growth accounting framework. A well-known example here is Brynjolfssen and Hitt (2003).

Third, the explanation that the high magnitudes are due to organizational capital gets some support from Bresnahan, Brynjolfsson, and Hitt (2002) who conducted a survey containing explicit questions on decentralization within firms. Black and Lynch (2001, 2004) and Caroli and Van Reenen (2001) do not find support for interactions between IT and organization, but they have less sophisticated measures of IT capital than Brynjolfsson and his colleagues. Bloom, Sadun, and Van Reenen (2005) find some support for the organizational capital hypothesis as they find much higher returns for the IT in US multinationals compared to non-multinationals than between statistically similar establishments in the UK.

Fourthly, there is a very wide range of estimates of the elasticity of output with respect to IT capital. The Stiroh (2004) meta-study is very useful for comparing the sub-set of studies considered here. He finds that the mean of the estimates across studies is about 0.05, which is well above the share of the IT stock in revenue as noted above. However, the estimates range from an upper end of over 25 per cent to minus 6 per cent.

This wide variation is in part driven by methodological choice, but also is strongly suggestive of heterogeneity in the IT coefficient by country, industry, and type of firm. Bloom, Sadun, and Van Reenen's (2005) findings of systematically different returns by ownership type and industry corroborate this. In particular they find that US firms receive a higher return from IT and this higher return is driven by the sectors that intensively use IT (the same sectors underlying the US productivity acceleration highlighted in Figure 2).

Finally, the evidence for spillovers is very weak. Most studies struggle to find convincing impacts from spillover effects. This suggests that the GPT effects stressed by the theorists may be somewhat exaggerated. While the spillover mechanism is pretty clear for innovation or R&D it is much less clear for ICT.[37]

What we do not know

None of the literature has produced convincing evidence of a causal impact on ICT on productivity for example, by analyzing a natural experiment. Even the more sophisticated studies rely on standard panel data techniques for dealing with endogeneity. In the economics of education there are some studies examining the impact of computers on school productivity, which use policy variation to try to address the endogeneity issue. Angrist and Lavy (2002) in a study of learning in Israeli schools, find that treating computers as endogenous shows that there may actually be a negative effect from ICT. Machin, McNally, and Silva (2006), however, did find some positive effects of ICT in their study of English schools. Despite the absence of a consensus, the attempt to find alternative credible instrumental variables should be a priority for future research.

Another area where more work is needed is specification of the types of complementary organizational practices in more detail. What are they? What determines their distribution? Why do some firms appear to be better than others at introducing these organizational practices? Is this the explanation for differences between the US and other OECD countries?

On a more mundane level, the micro studies have focused more on hardware than software because of the lack of good data. Using software as well as hardware, and building in communications, has been done much more systematically at the macro than at the micro level.

Another lacuna exists in establishing a solid link between micro and macro. For example, micro studies may tend to overestimate the benefits of productivity growth if the impact of ICT mainly comes from redistributing the quasi-rents between oligopolistic firms (for example, in finance). This would not occur of we had ‘true’ productivity measures, but the dependent variable is usually deflated sales divided by labour which mixes productivity and the mark-up. Some element of the mark-up is legitimate product quality, but others may simply be market power from other sources.

Finally, the most prominent studies are still US based. There is a need for more cross-country comparisons at the micro level to examine why there may be differential returns for similar firms in different countries.[38]

Conclusions

There has been significant progress made since the mid 1990s in the analysis of IT and productivity. The fall in the quality-adjusted price of computers has enabled researchers to build and analyse very large-scale databases that have revolutionized our understanding of the role of ICT and productivity. The proliferation of databases covering thousands of firms and decades of data has enabled significant intellectual advance.

In this chapter we have presented a very basic neoclassical framework (with a few extensions), which we think is helpful in considering the problem. There does seem to be some reasonable evidence of a strong firm level association between IT and firm performance (although causality has still to be convincingly demonstrated). We need a much greater understanding of the interactions between the technological and organizational dimensions of firm performance.

Table 1 Example of growth accounting: Contributions to U.S. Output Growth

(US Non-Farm Non- Government business Sector annual rates of change (percentage points))

	Category	(1) 1974-90	(2) 1995-99	Acceleration (2)-(1)
1	Output growth	3.13	4.76	1.63
2	Capital services:[b]	1.62	2.34	0.72
3	of which: ICT[a]	0.37	1.01	0.64
4	other capital	1.25	1.33	0.08
5	Labour Services	1.17	1.44	0.27
6	of which: hours	0.97	1.19	0.22
7	labour quality	0.2	0.25	0.05
8	Multi-factor productivity (MFP)	0.33	0.99	0.66
9	Average Labour Productivity (ALP)	1.44	2.56	1.12

Source: Derived from Jorgenson and Stiroh (2000a,b) Table 2

a. *Includes services of consumer computers and software, but not consumer communications equipment*

b. *Includes services of consumer durables*

Table 2: Macroeconomic studies

Authors	Country & level of aggregation	Data	Measure of ICT	Method	Key results
Gordon (2000)	US, 1972-99	Uses data developed by Oliner & Sichel (2000).	Distinguishes between computer hardware, software & communication equipment. Productive stocks are calculated for hardware using detailed BLS equipment data. From Oliner & Sichel (2000).	Builds on previous growth accounting exercises, decomposing output/hour according to (i) cyclical effects; (ii) contribution of IT-producing sector.	Finds no evidence of structural acceleration in productivity during 1995-9 after accounting for cyclical and IT producing sector effects.
Gordon (2003)	US, 1972-2002	Business cycle analysis uses quarterly BLS data on 4 sectors: non-farm private business, manufacturing, durables, non-durables.	Focus on Oliner & Sichel (2000) results.	Performs further business cycle decomposition Main argument is that role of IT investment is exaggerated. Stresses that productivity gains have occurred but source lies outside of IT alone.	Main arguments: (1) Results such as Oliner & Sichel (2000) assume an unrealistic instant pay-off to IT investment. (2) Micro evidence in retail suggests productivity revival is uneven – concentrated in new establishments only. (3) Cross-state comparisons do not exhibit the expected relationship between IT intensity and state productivity.
Gust & Marquez (2004)	13 OECD countries, 1993-2000	OECD national data and regulations database	2 measures: (a) Share of IT producing sectors in GDP (OECD); (b) IT expenditure: GDP ratio (World IT Service Alliance)	Models labour productivity growth as a function of IT and other controls (e.g. employment population ratio, country fixed effects). Also look at IT investment equations	IT production and (to a lesser extent) IT expenditure are associated with higher productivity growth. Labour and start-up regulation significantly retards IT (although no controls for country fixed effects)
Jorgenson (2005)	G7 Economies	van Ark *et al.* (2002) for	Investment in IT hardware	Detailed growth	Late 1990s surge in IT capital investment is

	(Canada, France, Germany, Italy, Japan, UK, US)	Europe BEA & BLS (US) Statistics Canada Jorgenson and Motohashi (2005) (Japan)	and software Uses internationally consistent prices following Schreyer (2000) and Wyckoff (1995)	accounting analysis of input per capita, output per capita and TFP. 'Capital quality' represented by capital input: capital stock ratio.	found across the G7. Declining contributions of non-IT capital offset effect of IT surge in Japan, France and Germany.
Oliner & Sichel (1994)	US, 1970-92	BEA & BLS	Computer hardware & software	Examines reasons for the (then) IT productivity puzzle. Addresses assumptions regarding returns to IT, measurement and focus on hardware alone.	Main conclusion is that puzzle is 'more apparent than real': level of IT capital is simply low (2% total capital circa 1993). Robust result even when varying assumptions on returns to IT and measurement.
Oliner & Sichel (2000)	US, 1972-99	BEA & BLS	Distinguishes between computer hardware, software & communication equipment. Productive stocks are calculated for hardware using detailed BLS equipment data.	Detailed growth accounting. Breaks down contribution to output growth according to income shares and input growth rates.	IT capital is 1.1% of the 4.8% output growth rate during 1996-9. By comparison, earlier periods (1974-95) show IT contribution as 0.5-0.6%. IT producing sectors also experienced acceleration at 40% of total MFP growth for 1996-9.
Oliner & Sichel (2002)	US, 1974-2001	BEA & BLS	As above.	Extends results from Oliner and Sichel (2000) to 2001. Uses multi-sector growth model to assess sustainability of IT-driven	Earlier results on contribution of IT using and producing sectors still valid despite the dot.com bubble. Model projections of 2-2.75% labour productivity growth/year over the next decade.

				growth and make projections.	
Oulton (2002)	UK, 1979-98	ONS data for national accounts. Note US producer price indices (adjusted for exchange rates) used to value ICT. Value of software adjusted upwards.	Computers, software, telecoms equipment, semi-conductors.	Growth accounting but with important modifications with respect to measurement (e.g. use of US PPI, valuation of software).	Revised approach suggests GDP growth is underestimated, e.g. growth in 1989-98 period is 0.3% greater following the 'high' software approach. ICT contribution to GDP growth increased from 13.5% in 1979-89 to 20.7% in 1989-98. ICT contributed 55% of capital deepening during 1989-98 and 90% from 1994-8.
Wolff (2002)	US industries, 1960-90	National Income and Product Accounts (NIPA) (employee compensation). BEA (tangible wealth). Census of Population (education)	Stock of Office, Computing and Accounting (OCA) equipment category in BEA capital data.	TFP and labour productivity equations, regressions relating computer investment to structural change	No evidence of positive links between computer investment and TFP or labour productivity growth. Computer investment positively associated with occupational and industry restructuring.

Table 3: Industry level studies of IT and productivity

Authors	Country and level of aggregation	Data	Measure of ICT	Method	Key Results
Basu *et al.* (2003) (see below for UK)	US	Manufacturing and Services, 1977-2000 (some only since 1987), BLS, BEA.	US data from the BLS capital input data disaggregated by industry. Among equipment, BLS provides additional detail for information processing equipment and software (IPES). IPES is composed of 4 broad classes of assets: computers and related equipment, software, communications equipment, other IPES equipment.	Objective to test the GPT hypothesis by focus on potential presence of unmeasured complementary investments and presence of TFP gains amongst IT-using and non-using sectors.	ICT capital growth negatively correlated with TFP growth in late 1990s (consistent with simple model of unmeasured complementary investments).
Basu *et al.* (2003)	UK	34 industries, 1979-2000. (BE, Bank of England dataset).	ICT capital services derived using US methodology (Jorgenson & Stiroh 2000a, b) hence geometric, depreciation rate with US prices converted to sterling. Note software levels multiplied by three.	See above.	ICT capital services growth positively correlated with TFP. However, ICT investment positively correlated with TFP suggesting scope for the GPT hypothesis (given shorter lags in the UK).
Berndt & Morrison (1995)	US industries	2-digit manufacturing, 1968-86	Define high tech capital as aggregate of office and IT capital. Covers 4 asset codes OCAM including: office and computing machinery; communications equipment; scientific and engineering instruments and photocopy equipment).	Aim is to examine diffusion and impact of high-tech capital Labour productivity and profitability equations.	Limited evidence of positive relationship between profitability and share of high-tech capital. High-tech capital share negatively correlated with MFP. Greater levels of high-tech capital associated with superior economic performance However, increasing rates of such capital

					within industries not necessarily associated with improved performance.
Chun & Nadiri (2002)	US 4-digit industry	NBER-CES Manufacturing Industry Database	Decomposes TFP growth in 4 computer industries	Uses hedonic price information to separate out TFP growth due to product innovation (i.e. quality improvements); process innovation (i.e. technological efficiency improvements) and economies of scale.	Computer industry TFP growth explained by product innovation (30%); process innovation (50%) and economies of scale (20%). Increasing role for product innovation during late 1990s. Computer industry contribution to aggregate productivity growth estimated to be 1/3 of total TFP growth.
Crepon & Heckel (2002)	France	Firm data aggregated up to 2-digit sectoral and macro level, 1987-98	OCAM - office, computing and accounting machinery. Comes from tax declarations of 300,000 French firms (outside financial sector).	Growth accounting exercise	ICT contributes 0.7%/annum on average (0.4% from production of ICT, 0.3% from capital deepening). Av. value added growth 1987-98 is 2.6%/annum. Share of ICT capital much higher than suggested by French National Accounts (Cette, Mairesse, & Kocoglu, 2000)
O'Mahony & Vecchi (2003)	UK & US industries	UK (24), US (31) 1976-2000	ICT capital stock built from supply and use tables.	TFP regressions including heterogeneous panel estimates	LR effect of ICT above its factor share.
Oulton & Srinivasan (2003)	UK industries	34 industries 1970-2000 (BE Dataset)	ICT capital stock built from supply and use tables	Growth accounting, TFP and labour productivity regressions	ICT capital deepening has positive and significant effect post 1990 (accounts for large proportion of 1990s productivity growth)
Stiroh (2004)	US 2-digit (61 industries)	BEA Industry data on output,	(1) IT capital stock comprising computer hardware	(1) Meta-analyses of 20 existing studies	(1) IT elasticity predictable based on approach and

		investment and capital stocks.	and software. (2) Telecoms equipment as separate category of capital.	based on methods, type of data and resulting IT elasticity. (2) 'Full disclosure' regression analysis of BEA data using many alternative approaches and reporting all findings.	estimation method. Mean estimates include 0.042 (value-added) and 0.066 (gross output). (2) BEA data regressions indicate IT elasticities fall as estimation moves from levels to methods accounting for unobservables. System GMM provides the most sensible estimates (0.05 IT elasticity).
Stiroh (2002a)	61 US 2-digit industries (1987-2000) 49 US 2-digit industries (1977-2000)	BEA data on industry gross output, labour input and intermediate input. BEA Tangible Wealth Survey used to build capital stocks.	IT capital built up from wealth stocks on computer hardware (8 types); software (3 types); and communication equipment. Capital Service Flow measure constructed by aggregating individual capital stocks using asset-specific prices.	Uses pre-1995 IT intensity (both discrete and continuous measures) to assess whether acceleration argument for IT-using industries is valid. Decomposes labour productivity growth according to 3 sectors: IT-producing and IT using industries, and those 'isolated' from IT.	Pre-1995 IT intensity related to patterns of acceleration for discrete and continuous measures. Acceleration for IT intensive industries approximately 2% more than other industries. Decomposition finds that IT-using industries contribute 0.83% of total acceleration with IT-producing industries accounting for 0.17%. Isolated industries made a -0.21% contribution.
Stiroh (2002b)	US 2-digit Manufacturing (18 industries *15 years)	BLS multifactor productivity database for manufacturing (18 industries from 1984-1999)	ICT capital including total value of hardware, software and telecommunications equipment. Computer capital defined as hardware and software assets only.	Tests a key spillover hypothesis: that ICT impacts on TFP if network effects or externalities are present. Uses traditional difference-in-difference and traditional Labour Productivity and TFP	Finds some positive effects of ICT on average labour productivity but not TFP. Telecommunications capital has a negative association with productivity. In general, no strong evidence of spillover-type effects of ICT on productivity.

				regressions to test above hypothesis.	
Van Ark *et al.* (2002)	12 EU countries and US (EU countries include Austria, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, UK)	Manufacturing and Services, 1980-2000 (Using input-output tables)	(1) Broad definition of ICT as comprising the whole category of office and computer equipment - including peripherals (2) Separate investment series on ICT investments used where available (applies to most assets for Denmark, France, Netherlands, Italy, UK, only to specific assets for Germany and Spain). (3) Used a Commodity Flow Method to fill gaps. This supply side method first computes total amount of ICT commodities available in a specific year as value of total ICT production less ICT exports plus ICT imports.	Concentrates on building comparable ICT investment and ICT capital data across EU and US then employs standard growth accounting and labour productivity equations.	Similar growth rates ICT real capital formation and capital services for US and EU. Investment patterns similar – office equipment grew strongly in the 1980s and from the late 1990s. Growth of communication equipment and software accelerated after 1995 (more so in the US). ICT investment share levels lower in the EU - 2/3 of US level throughout the period. Relative contribution of ICT to EU labour productivity growth close to US but slowdown in EU growth reduces the absolute contribution. Stronger TFP effects for ICT-producing sectors in the US during the 1990s.
van Ark & Inklaar (2005)	US and European industries (France, Germany, Netherlands, UK)	60 industries, 1987-2004. Specially constructed GGDC dataset.	Investment series for different types of IT-related capital expenditure.	Growth accounting equations for macro-level data. Labour productivity equations for industry data ('shift-share' approach following Stiroh (2002b).	Lower IT-contribution to EU growth has continued through early 2000s. US-EU differential increased following strong labour productivity gains in US market services (i.e. non-government sector).

TFP equation to test for spillovers.	No evidence of IT spillovers to TFP.
	Hypothesis of U-shaped IT returns pattern: initial ‘hard savings’ followed by experimentation period then ‘soft savings’ as capital complementarities develop.

Table 4: Firm-level studies of IT and productivity

Authors	Country and level of aggregation	Data	Measure of ICT	Method	Key Results
Atrostic and Nguyen (2005)	US establishments	Computer Network Use Supplement (CNUS) of the 1999 Annual Survey of Manufactures (ASM). Approximately 30,000 plants.	Discrete indicator of whether establishment uses a computer network.	3 factor production function (incorporating materials). Endogeneity of networks addressed by explaining network presence as function of past performance (2SLS).	OLS indicates that labour productivity is 3.7% higher for network-using establishments. 2SLS indicates a 7.2% effect. Lower productivity in earlier periods associated with networks. Interpreted as evidence that establishments may use networks to catch up.
Black and Lynch (2001)	US establishments	Educational Quality of the Workforce – National Employers Survey (EQW-NES) matched with Longitudinal Research Database (LRD) 638 establishments in manufacturing, 1987-1993	Proportion of non-managers within establishment using computers. Many controls for workplace practices and characteristics (education, union presence) to account for complementarities.	Cross-sectional Cobb-Douglas production function. 2-step fixed effects approach (i.e. second stage involves regressing firm effects on a set of explanatory variables).	IT variable significant and positive in cross-sectional production function. IT significant in 2-step within estimator, but not GMM version.
Black and Lynch (2004)	US establishments	1993 and 1997 waves of the EQW-NES. Panel of 766 establishments (again matched with LRD). 284 establishments in the balanced panel.	Proportion of non-managers within establishment using computers. Again, controls for other (complementary) workplace practices and characteristics.	Cross-sectional Cobb-Douglas production functions for 1997 wave. Includes interaction effects in production functions. Production functions with	IT variable significant and positive in cross-sectional production function. Interaction terms of IT variable with workplace practices and characteristics not significant.

				fixed effects (for balanced panel). Uses estimates in a decomposition of MFP growth (benchmarked against BLS estimates).	IT variable significant in fixed effect model for balanced panel. Workplace innovation makes 1.4% contribution to MFP growth (approximately 89% of total MFP growth)
Bloom, Sadun, & Van Reenen (2005)	British establishments 1995-2004 (unbalanced panel)	7,000 establishments	IT capital constructed from 3 ONS surveys (FAR, Quarterly Capital expenditure Survey, BSCI). PIM	Estimation of panel production functions and TFP regressions. Compare OLS, Within Groups, GMM and OP.	IT significant impact on productivity. Effect greater for US than non-US multinationals or domestic firms. US effect also stronger in IT intensive industries.
Bloom, Draco, Kretschmer and Van Reenen. (2005)	Britain (1994-2004),	About 3,000 firms in 1994-2004	Constructed using Harte-Hanks hardware and software data (recorded at business site level). Measures include: (i) Value of IT hardware (ii) PCs/employee	Production functions estimated by OLS, within groups and GMM . Tests for heterogeneity of IT impact across different firm characteristics (e.g. size, sector, time period). Tests for spillovers at the regional and industry level. Reduced form investment models.	Significant and positive effect of IT on productivity (elasticity with respect to output 0.035 on within-groups specification) No evidence of IT spillovers at industry or region level.
Bresnahan, Brynjolfsson, & Hitt (2002)	US firms across all types of industries.	331 firms (NB survey asked managers about characteristics at level of the 'typical establishment')	ICT capital calculated using CII data on firm computer hardware inventories only. Author's (cross-sectional) survey	Correlation analysis of relationship between potential complementary inputs. Input choice functions.	Complements (IT, organization and skills) significantly and positively co-vary Skills and organization

			of organizational practices and skills circa 1995-6. Compustat accounts information.	Production functions with interaction terms.	significant as determinants of IT demand. IT-Skill and IT-Organization interaction variables significant in production function.
Brynjolfsson, Hitt, & Yang (2002)	US firms	1987-97 Compustat firms matched with CII data and author's (cross-sectional) organizational practices survey. Final sample features 272 firms with matched data and 2,097 observations in total.	CII measure of the market value of computer equipment at a firm (calculated based on replacement cost).	Estimates market value equation focusing on how IT and organizational practices represent intangible assets. OLS, Least absolute deviations, Fixed and Random Effects estimation of market value equation. Also, use long difference specification. Nonparametric plot of relationship between organization, ICT and market value.	Key organizational characteristics correlated with ICT capital but not physical capital. ICT capital associated with higher market value. Interaction term between organization and ICT significant – firms with combinations of ICT and good organizational practices have the highest market value.
Brynjolfsson & Hitt (2003)	US firms	527 large Compustat firms 1987-94	Computer capital stock CII (Harte Hanks) value of total IT stock; IDG (firms stated value of mainframes plus no. PCs)	OLS, short and long differences. Production function and TFP equation	In long differences IT coefficient above IT capital share in revenue
Dewan & Min (1997)	US firms	Computerworld data matched to Compustat. 1,131 observations (unbalanced) with maximum of 304 different firms observed in a single year	Market value of computer hardware and labour expenses for IT staff.	CES-Translog production functions.	Some evidence of excess returns to IT capital.

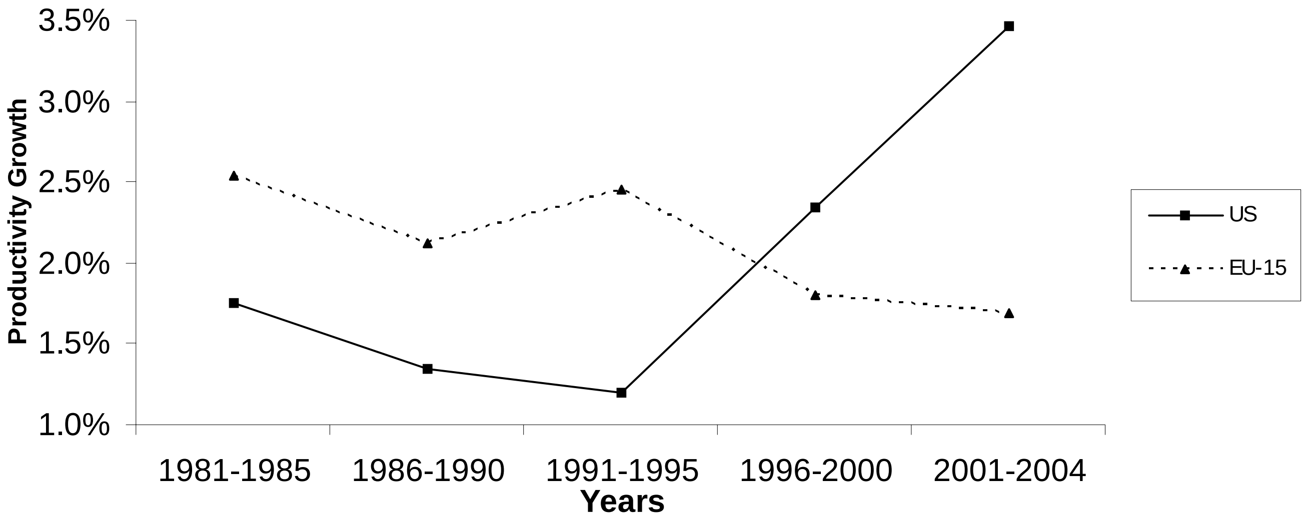
		1988-92.			
Forth & Mason (2003)	UK firms	1997-9 International Benchmarking Survey; 308 firms c. 900 observations	Categorical indicators of different types of ICT	OLS and IV estimation	Generally positive impact; interactions with skill shortages
Gilchrist, Gurbaxani, & Town (2003)	US firms, 1986-1993	CII matched to Compustat. Unbalanced panel of 580 firms.	IT hardware value. PCs/employee.	GMM estimation of production function. Regressions of Solow residual on inputs.	IT coefficient approximately equal to cost share; PCs have additional impact in durable goods sectors. Growth of PCs significant in Solow residual regression, also with additional impact in the durable goods sector.
Greenan, Mairesse, & Topiol-Bensaid (2001)	French firms, 1986-94	SUSE (System of Unified Statitics on Enterprises) and ESE (Employment Structure Survey) Approximately 3,000 manufacturing firms and 2,500 in services.	Value of office and computing equipment No. of specialized workers (computer, electronics, research and analysis staff),	Mainly examines correlations between IT, R&D and skills. Some production function estimation.	IT effect is not significant when firm fixed effects are included. Share of blue-collar workers falls with increase in IT (for all indicators).
Greenan & Mairesse (1996)	French firms, 1987-93	TOTTO (specialized survey of techniques and organization of work) matched to INSEE firm database for 1987, 1991, 1993. Approximately 3,000 observations/year.	No. employees using computers at work (calculated from sample)	OLS Cobb-Douglas production function, no fixed effects	IT coefficient stable across models for all 3 years. Coefficient of approximately 0.20.
Gretton, Gali, & Parham (2004)	Australian firms	Australian Business Longitudinal Study Panel of three years 1988-9; 1993-4; 1998-9 Sample sizes not	Binary indicator and duration dummies	OLS Productivity growth equation. Controls include lagged level of productivity, capital growth. Separately for 8 sectors	IT positive in most, specifications, significant in only 2 specifications

		clearly stated.			
Haltiwanger, Jarmin, & Schank (2003)	US and Germany	Matched ASM and CNUS for the US, 1999-2000. 22,000 observations. IAB manufacturing sector panel for Germany, 2000-1. 3,500 observations used in regression analysis.	Total investment in computers and peripheral equipment (US). Total investment in information and communication technology in previous business year (Germany) Proportion of employees with internet access (US and Germany)	Compare the productivity outcomes for similar IT intensive firms in both countries. High IT intensity defined by whether firms are in the top 25% viz IT investment and internet access. Assumes that the most IT intense firms have a propensity to 'change technologies'.	IT-intensive US firms exhibit greater productivity dispersion, particularly amongst younger businesses.
Hempell (2005)	German and Dutch firms	1998 CIS (but with lags as IVs); distribution and business services; Netherlands 972; Germany 995	ICT expenditure converted into a stock	GMM-SYS (but instruments appear invalid as Sargan-Hansen test rejects)	Significant ICT effect; many complementarities
Hendel (1999)	US establishments	Comtec survey of 7,895 establishments (Conducted 1994 and 1998). Note studies only 240 banking and insurance establishments from 1988 survey. PC price and characteristics data (used by Berndt & Griliches 1993).	Detailed information PC hardware, including brand, type, quality.	Explicit model of establishment-level demand for differentiated types of PCs. Based on buyers making multiple discrete choices. Task-based model of why establishments choose different types of computer equipment.	Estimated return on PC investment calculated as 92%. 10% increase in performance-to-price ratio for microprocessors estimated to raise user surplus by 2.2%.
Lehr & Lichtenberg (1998)	US govt agencies, 1987-92.	BLS Productivity Measurement Program (Data on agency output and productivity). CII 44 agencies in matched data.	Replacement value of computer capital (via CII).	Production functions based on BLS estimates of the output of government services (44 agencies).	Excess returns to computer capital (with 0.061 co-efficient on computer capital compared to 0.014 share of IT capital in total cost).
Lehr &	US	Enterprise Survey	Replacement value	Production	Excess returns to

Lichtenberg (1999)	1977-93	(Census Bureau) Auxiliary Establishment Survey Compustat CII Matched sample includes 5,00 firms.	of computer capital (via CII) Investment in computer equipment (Census Bureau)	function regressions, including terms for specific types of equipment. Inventory regressions (i.e.: test whether computers facilitate just-in-time style production strategies).	computer capital still found after including firm fixed effects. These returns peak in 1986-7. Negative association between computer capital and inventories.
Lichtenberg (1995)	US	190 to 450 firms	Computer and non-computer capital stock, ICT and non-ICT labour	OLS, no IV or fixed effects	In long differences IT coefficient above cost share
Matteucci *et al.* (2005)	Germany, Italy and UK	Germany IAB 3,168 observations 1997-2000 Italy 'Capitalia' manufacturing firms 1995-2000 3,918 observations (unbalanced) and 1,119 (balanced) ABI linked with 2001 ONS E-commerce survey 2,422 observations.	Lagged ICT investments plus instruments based on firm training patterns (Germany) Single year of ICT investment information Duration of internet access at firm and proportion of workers using a PC	Regressing firm fixed effects on various characteristics to explain determinants of productivity. TFP Equation Cross-sectional Cobb-Douglas production function	Significant effect of ICT in manufacturing but not services. Weakly significant effect of ICT (10% level). Significant impact for PCs/worker in service sector
Wilson (2004)	US 1998	1998 ACES matched with Compustat firms 3,000 firms in matched sample.	Total Computer and Peripheral Equipment Investment as measured in ACES	Looks at the effects of different capital types on variously defined measures of TFP. Uses to interaction effects to examine complementarities and substitutability between capital types. Calculates	Positive effects of computer capital on TFP. 'High-tech' capital complementary with 'low-tech' capital. Different types of capital are substitutable within their technology class (i.e. high-tech vs low-tech).

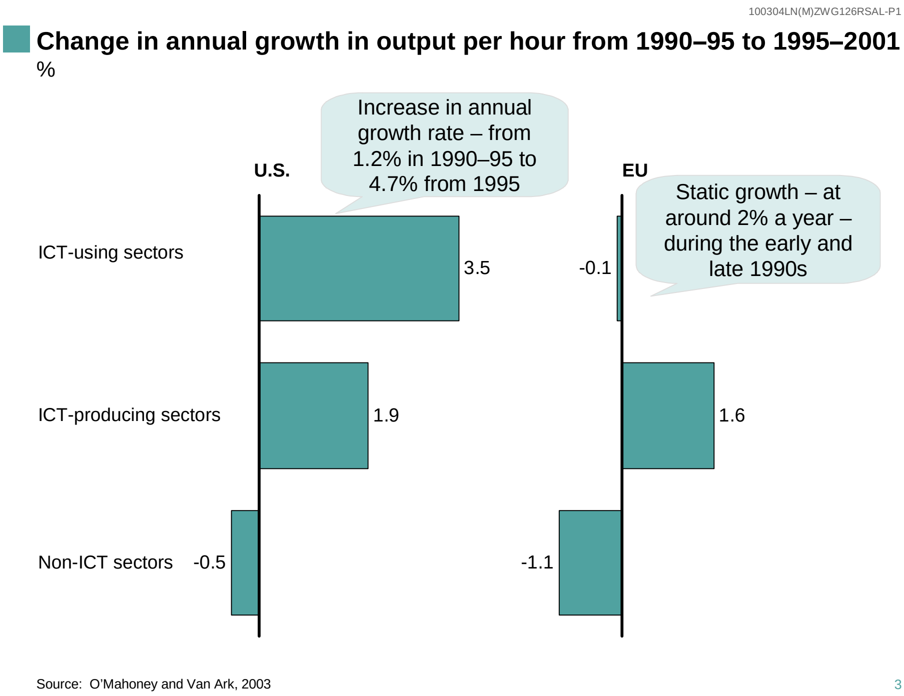
marginal products for different capital types.	Marginal products for computers, communication equipment and software are higher than those suggested by BLS rental prices.

Figure 1: Annual growth rates of real GDP/hour



Source: Groningen Growth and Development Centre

Figure 2: US and European acceleration in productivity growth (market sector)



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[1] Of course, we could consider multiple sub-divisions of the capital stock and other factors of production.

[2] The inputs should be expressed in terms of the flows of services that the input stocks create, which feeds into the flow of output. See the Data Section for more discussion.

[3] Helpman and Trajtenberg (1998); Yang and Brynjolffson (2001).

[4] Note that finding a positive coefficient on the interaction is not sufficient to establish that the two factors are complementary in the Hicks-Allen sense. A positive coefficient makes Allen elasticity more likely, however.

[5] See Griliches (1992); Bloom, Schankerman, and Van Reenen (2005).

[6] Such as changes in the tax price, see Bloom, Griffith, and Van Reenen for examples from R&D.

[7] Stiroh (2004); Bloom, Sadun, and Van Reenen (2005) and Hempell (2005).

[8] Although note that the bias will be towards zero and researchers in the micro literature generally find IT coefficients that are higher than we would expect.

[9] Additional instruments dated *t-3, t-4*, etc. become available as the panel progresses through time.

[10] The conditions are that the initial change in productivity is uncorrelated with the fixed effect $E(\Delta y_{i2}\eta_i) = 0$ and that initial changes in the endogenous variables are also uncorrelated with the fixed effect $E(\Delta x_{i2}\eta_i) = 0$.

[11] For notational simplicity we abstract from plant age, but we implement this in the estimation routine along the same lines as Olley and Pakes (1996).

[12] Numerous extensions to the basic OP methodology have been suggested. First, we consider the additional selection correction originally suggested by the authors. Second,

Levinsohn and Petrin (2003) suggest using intermediate inputs as an alternative proxy for the unobserved productivity term. This has attractions for plant level data where investment is zero in a non-trivial number of cases. Ackerberg, Caves, and Frazer (2005) and Bond and Soderbom (2005) emphasize the identification problems underlying the original OP set up, which implicitly requires variation in firm specific input prices. Bond and Soderbom argue for the GMM approach discussed in the previous sub-section, which is identified in the presence of differential adjustment costs.

[13] If one is willing to work with an aggregate measure of capital, extra care must be taken in aggregating the different asset types, but we will abstract from this issue in this context. For a detailed treatment of the issue see Oulton and Srinivasan (2003).

[14] The main issues involved in the measurement of IT flows with industry and firm level data are discussed in detail in the next paragraphs.

[15] Rental prices are also very important in constructing Tornqvist aggregate service flows of assets of different types. Rental prices rather than asset prices are used as weights to account for differences in the rate of return to capital, the rate of economic depreciation, the rate of nominal appreciation of assets and their tax treatment.

[16] Oulton and Srinivasan (2003), O' Mahony and de Boer (2002), van Ark *et al.* (2002))

[17] In this framework IT is defined as the aggregation of the different IT investment series produced by the BEA, i.e. mainframe computers, personal computers (PCs), direct access storage devices, printers, terminals, tape drivers, storage devices.

[18] The BEA also makes adjustments to reflect trade costs and transportation margins (to convert into purchaser value).

[19] These two tables represent the main sources for the construction of the IT capital stocks used in Jorgenson and Stiroh (2000a, 2000b), Jorgenson, Ho, and Stiroh (1999),

Stiroh (2002a, 2002b, 2004), Oliner and Sichel (2000), Bosworth and Triplett (2002), Basu *et al.* (2003), Nadiri and Mun (2002), Chun and Nadiri (2002), Berndt and Morrison (1995).

[20] The IT deflators are described in Grimm, Moulton, and Wasshausen (2002).

[21] The basic principle of the hedonic deflators is as follows. The estimated prices of specified characteristics (e.g. speed for PCs) are used to quality adjust the price of a newly introduced model so that it is consistent with the discontinued model. For software the deflators are derived from PPI's, a BEA cost index, and a BLS employment cost index (ECI) and are applied to three subcategories (pre-packaged, own account, and custom software). A detailed description of the methodologies can be found in Landefeld and Grimm (2000).

[22] This is fully described in Fraumeni (1997). Until the 1999 revision, the estimated depreciation rates for computers were cohort and asset specific, taken from studies by Oliner. With the 1999 revision of the National Income and Product Accounts (NIPA) a new depreciation rate was introduced for PCs only. The value is 0.3119, based on Lane (1999), assuming that the value of a PC declines to 10 per cent of its initial value after 5 years. As noted by Doms *et al*. (2004), this schedule incorporates the full loss in PC value as it ages, capturing both depreciation and revaluation. Starting from the 2003 revision of the NIPA - and based on new evidence in Doms *et al*. (2004), the depreciation rate for PCs has been changed to 0.34.

[23] Other differences between the BEA and the BLS estimates relate to the construction of the aggregate capital stock measures. The BLS uses the Jorgenson methodology to build a service measure of capital stocks (also defined as an estimation of 'productive capital stocks') instead of the BLS wealth measure (the methodology is summarized in

http://www.bls.gov/web/mprcaptl.htm).

[24] Note for the UK O'Mahony and de Boer and the Bank of England dataset introduced in Oulton and Srinivasan (2003).

[25] In this context IT is defined very broadly as comprising the whole category of office and computer equipment - including peripherals such as printers, photocopiers, etc - radio, TV and communication equipment, and software.

[26] Since the information on occupational activities by industry is used to produce an asset by industry matrix, this embedded relationship between industry IT flows and employment may introduce dangerous spurious correlations. For example, this issue may put at risk studies that use the data to investigate correlations between capital mix and employment mix choices (Chennells and Van Reenen, 2002). Moreover, the specific occupational categories used to break down the IT flows by industry are not published. Bosworth and Triplett (2002) note that the latest year for which the BEA flow table was used to allocate IT capital by industry is 1992. Another problematic issue is the measurement of software investments especially custom-made software (Dedrick, Gurbaxani, Kraemer (2003).

[27] The country specific matrices of IT investments by industries are interpolated for intermediate years. For longer gaps in the data the Commodity Flow Method is employed. This supply side method first computes the total amount of ICT commodities available in a specific year by taking the value of total ICT production plus the net value ICT imports less ICT exports). Then the shares of investments across the different industries are allocated using as weights the shares of total investments over production minus exports plus imports computed from the input output tables

[28] Interestingly, the higher shares reported by Crepon and Heckel does not seem to be

related to selection issues.

[29] Several adjustments are made to apply the data in a production function framework. In Brynjolfsson, Bresnahan, and Hitt (2002) the nominal values are deflated using price information. Brynjolfsson, Bresnahan, and Hitt (2002) use prices developed by Robert Gordon (19.3% yearly changes). In Brynjolfsson and Hitt (2003) the data are transformed from wealth stocks (market value of the assets) into productive stock (the value of assets based on output capability) multiplying the wealth stocks by the annual aggregate ratio of the productive stock to the wealth stock of computer assets computed by the BLS (1,2). The CII data have been extensively used in other research on productivity. Some recent examples include Lehr and Lichtenberg (1999) - where CII data are combined with additional census based data on firm level IT investments - and Gilchrist, Gurbaxani, and Town (2001) – where CII data are used in the context of TFP growth regressions. More recently, Bloom, Draca, and Van Reenen (2005) used a similar type of data (detailed information on the volume of IT equipment existing in a specific site of a firm, collected via telephone survey) to analyse the impact of IT on productivity in the UK economy.

[30] Greenan and Mairesse (1996) use the questions on IT use by workers collected in the framework of the French survey TOTTO (Enquete sur les techniques et l'Organisation du Travail) to build firm level measures on computer use, which they match with the INSEE firm database. Clearly, the worker- level information requires specific assumptions regarding the degree of representativeness of the employees surveyed.

[31] Maliranta and Rouvinen (2004) use as IT measures the percentage of employees in Finnish firms using computers and/or LAN and Internet systems. These data are collected in the framework of Statistics Finland's Internet use and e-commerce in

enterprises surveys. A similar measure is collected in the UK in the E-Commerce survey (Criscuolo and Waldron 2003).

[32] These studies combine basic information on the existence of computer networks within a firm with more detailed data on specific types of IT resources such as fully integrated ERP software.

[33] These data require very specific assumptions on the depreciation or the growth patterns of the capital stocks. If we assume full depreciation ($\delta = 1$) then the investment flows represent a valid proxy for capital stocks. This is the choice implicitly made by Doms *et al*. (2002) in a study focusing of the role of IT in US retail sector productivity, where the ratio of IT investments over total investments (drawn from the 1992 Asset and Expenditures Survey) is used to proxy for IT capital intensity for some 2000 retail firms. The same type of measure (IT investment share in total investments) is employed by Haltiwanger, Jarmin, and Schank (2003) in a comparison of IT effects in the US and Germany. Wilson (2004) uses a slightly more sophisticated framework to exploit the 1998 ACES on detailed firm level investments in IT (and in 54 other types of assets) in a production function context. He rewrites the PIM formula as:

$$K_{t-1} = (g_t + \delta) * I_t$$

$$g_t = \frac{\Delta K_t}{K_{t-1}}$$

He then assumes that in the steady state *g* should be approximately equal to zero, and states a direct proportionality between stocks and flows, running through the depreciation rate.

[34] Bloom *et al.* (2005) use four different surveys on micro level IT investments in the UK economy collected by the Office of National Statistics for the years 1995-2003.

Hempell (2005) employs IT investment data from the Mannheim Innovation Panel in Services (MIP-S), collected by the ZEW on behalf of the German Federal Ministry of Education and Research since 1994.

[35] Bloom *et al*. (2005) build the initial conditions of the PIM assuming a direct proportionality between industry and firm level capital stocks. Defining the first time a firm appears in their sample as *Υ,* they allocate the industry level capital stock to each firm according to investment weights, i.e.:

$$K_{i,r}{}^{j} = \left(\frac{I_{i,r}{}^{j}}{\bar{I}_{r}{}^{j}} \right) \overline{K}_{r}{}^{j}$$

where $\overline{K}_{r}{}^{j}$ and $\bar{I}_{r}{}^{j}$ represent respectively total IT capital stock and investment for industry *j* in year *r*. For all periods following year *r*, they follow the standard PIM recursion. Under the assumption that investment expenditures in capital goods have in the past grown at a similar, constant, average *g* for all firms,[35] Hempell (2005) writes the basic PIM equation as:

$$K_{i,r}{}^{j} = I_{i,r} \sum_{s=0}^{\infty} \left[\frac{1-\delta}{1+g} \right]^{s} = \frac{I_{i,r}}{g+\delta}$$

[36] Oulton (2002) shows that the contribution of ICT to UK productivity growth increased from 13.5% in total growth in 1979-1989 to 21% in 1989-1998. This is less than the US experience, but greater than the European average.

[37] Griliches's (1992) survey and some recent contributions (e.g., Bloom, Schankerman, and Van Reneen 2005) provide compelling evidence about the importance of spillovers from R&D.

[38] Bloom *et al*. (2005) have developed a UK dataset on IT and firm performance; they plan to produce comparable data for France, Germany, and the US.

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