Information and Communication Technology and Economic Performance

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Abstract: In this paper we review the evidence on the role, contribution and causal nexus between ICT and economic performance. We classify the theoretical underpinnings of ICT and economic growth into *four* broad categories: exogenous growth models that follow Solow (1956); endogenous growth models without explicit endogenous technological change; endogenous growth models with explicit endogenous technological change, and the technology transfer model. Each approach generates different testable hypothesis which are reviewed. Furthermore, we appraise the current evidence on the relationship between ICT and economic performance.

JEL Classifications: O14, O33, O47 and O57

1. Introduction

Global Information, Communication Technology (ICT), driven by the electronic computer and its applications has grown over the recent past and permeates much of everyday life[1]. The *Digital Planet 2002* reports statistics on 55 countries[2] and identifies a typical country as having ICT spending increases of 5 percent per annum.

Both the OECD and the IMF have produced a large body of research which has sought to measure, codify and develop policy initiatives based upon ICT as the new 'engine of growth' see for example, OECD (2000a,b, 2001a,b, 2002a,b, 2003, and 2004) and IMF (2001)[3]. In addition Oulton (2001), Parham, *et al.* (2001), Pilat (2002), Pilat and Lee (2001), Pilat *et al.* (2002), Daveri (1999, 2000, 2001, 2002) and van Ark *et al.* (2002a,b) have provided some, typically, region/country-specific evidence on the contribution of ICT to economic growth.

These recent papers, however, generally relate to 'research at the frontiers' with minimal/nil 'survey of the literature' content[4]. Both the 2001 and 2002 OECD Ministerial meetings reiterated the importance of ICT for growth performance and requested the OECD to continue research in this area. This, in part, has lead to the latest OECD contribution in this area *The Economic Impact of ICT,* OECD (2004).

It seems timely, therefore, to review the evidence on the role, contribution and causal nexus between ICT and economic performance. In this survey we provide both a framework for theoretical discussions[5], including alternatives to the neoclassical models of Solow (1956) and Swan (1956), and importantly a review of the current evidence on the relationship between ICT and economic performance. This is vital as many developing countries are attempting to bridge the *Digital Divide* by emulating those who now top the various ICT league tables. However, this can be potentially futile if there is little understanding of what is being done and why and the causal nexus. For example, *Digital Planet 2002* shows New Zealand as one country that is 'leading the way' (since 1999) in terms of the greatest percentage of GDP spent on ICT[6], 14.4 percent in 2001. However, using the (log) ICT spending data from *Digital Planet 2002* as an approximate measure of the local ICT sector, the correlation between ICT spending and (log) GDP for New Zealand over the period 1993-2001 is only 0.05. This finding is reinforced by those of Carlaw and Oxley (2004) who conduct an empirical analysis on the available ICT diffusion data in New Zealand questioning whether Total factor Productivity (TFP), growth rates in industrial sectors are correlated with the diffusion rate of ICT and conclude that, at best, TFP growth is not correlated with ICT diffusion and at worst the two are negatively correlated. Their findings are consistent with the theoretical predictions of Lipsey, Carlaw and Bekar (forthcoming 2005) that the introduction of General Purpose technologies that require large structural adjustments with many complementary innovations will have diffusion rates that are negatively correlated with TFP growth. Is this typical for all countries? Does it matter what time periods are considered? Does it matter what data are used? Does it matter which statistical/econometric methods are utilized to investigate the relationship between ICT and economic growth?

In this survey we will consider a range of theoretical models which show a potential role for new technologies like ICT to contribute to economic growth and development. That section will act as a basis for a critical review of the empirical evidence discussed in Section 4. In particular, in Section 2.1 we review the role of technology in the Solow-Swan model, which forms the basis of most neoclassical models of economic growth. Testable implications from the model will be identified and used in a critical review of the empirical literature in Section 4. In Section 2.2, endogenous growth models without explicit technological change will be introduced.

Section 2.3 extends these to the endogenous technological change models of Helpman and Trajtenberg (1994 a, 1994 b), Aghion-Howitt (1992, 1998), Lipsey Bekar and Carlaw (1998), and Lipsey, Carlaw and Bekar (2005). Section 2.4 outlines the technology transfer model of Bernard and Jones and highlights the role of cross-country convergence as an implication. In each of 2.2-2.4 we identify model-specific testable implications on the relationship between ICT and economic performance to be used in Section 4. Section 3 of the paper considers data-related issues; more specifically which datasets have been used by researchers and what are available to use when testing the relationship between ICT and economic growth. In Section 4 we critically review recent results on estimating and testing ICT effects on the economy and Section 5 concludes.

2. Theoretical underpinnings

We classify the theoretical underpinnings of ICT and economic growth into *four* broad categories: (i) exogenous growth models that follow Solow (1956), (ii) endogenous growth models without explicit endogenous technological change , (iii) endogenous growth models with explicit endogenous technological change, and (iv), the *Technology Transfer Model* (Cross-Country Convergence). Each of these modeling frameworks generates different testable hypothesis.

2.1 The Solow- Swan Growth Model

The Solow (1956) model forms the basis of most discussions of the economic growth process and the foundation of much of the empirical literature including that on 'convergence', see Islam (2003). The basic model's assumptions and predictions can be found in any introductory macroeconomics text, but are included here as Appendix 2.

Some important properties of the approach include a unique steady-state equilibrium where there exists sufficient saving to maintain the level of investment necessary to sustain the current capital-labour ratio. Uniqueness[7] stems from restrictive assumptions with respect to the production function, which we will see are relaxed in the endogenous approaches discussed below. Technical progress normally enters as a *Harrod-neutral* process which shifts the production function permitting output per capita to grow at a constant rate.

2.1.1 Testing the relationship between ICT and growth using the Solow model

The relationship between technological progress and economic growth is commonly tested using the 'growth accounting approach[8]' which assumes the economy is at its steady state equilibrium. Final output is generally modelled via a Cobb-Douglas equation:

$$Y = AK^{\alpha}L^{\beta} \text{ where } L = \{L_1, L_2 ... L_i\} \text{ and } K = \{K_1, K_2, ... K_j\} \qquad (2.1)$$

Where the growth rate of output is represented as:

$$\frac{\dot{Y}}{Y} = TFP + \alpha\frac{\dot{K}}{K} + \beta\frac{\dot{L}}{L} \qquad (2.2)$$

Given values of α and β[9] we could test the relationship between economic growth and ICT by examining the correlation between TFP and the pattern of ICT diffusion, or test the significance of ICT by its contribution to the growth of final output, or the growth of aggregate inputs.

Equation (2.2) could also be written to emphasize the decomposition of productivity growth per person hour into capital deepening and TFP growth:

$$\frac{\dot{Y}}{Y} - \frac{\dot{L}}{L} = TFP + \alpha\left(\frac{\dot{K}}{K} - \frac{\dot{L}}{L}\right) \qquad (2.3)$$

The second term on the right-hand side of (2.3) represents the ‘capital deepening’, which characterizes the contribution to growth from capital goods. Within this framework van Ark (2002) decomposes the TFP term into what that model interprets as technological changes[10] generated from the production of ICT (TFP^{ICT}) and TFP contribution from other industries (TFP^{other}):

$$TFP = \sum_j \bar{\gamma}_j^{ICT} TFP^{ICT} + \sum_j \bar{\gamma}_j^{other} TFP^{other} \qquad (2.4)$$

where γ_j^{ICT} represents the output shares of ICT-producing industries, and TFP^{ICT} the TFP growth in ICT-producing industries, and thus $\gamma_j^{other} TFP^{other}$ represents the contribution to aggregate TFP from non-ICT industries.

Given the lack of disaggregate ICT data for most countries, an alternative approach is to approximate the rate of productivity growth in each industry by the inverse of the change in the price of output, plus a weighted average of the growth rates of input prices with value shares of the inputs as weights, namely the price dual approach (see van Ark 2002).

A summary of the growth accounting studies’ results are presented in Section 4 below. *In general, the test results contradict the theoretical predictions*. With the adoption of ICT being recognized as some form of technological progress, significant increases in the proportion of ICT in national production does not always lead to significant increases in final output. Many EU countries, in fact, experienced a slowdown in economic growth in the last two decades namely the ‘Productivity Paradox’ or the ‘Solow Paradox,’ where Solow states ‘…you can see computers everywhere, but in the productivity statistics… (Solow 1987).’

2.2. Endogenous Growth Models with no Endogenous Technological Change

Endogenous growth models come in many forms and they challenge the underlying assumptions of the Solow approach by endogenously formulating some of its neglected aspects including social, organization structure or market structure. In this section we concentrate on the former.

In the Solow model growth occurs due only to an assumed constant rate of exogenous technological progress. In contrast, some models of endogenously sustained economic growth generate that growth through assumptions of externalities and non-decreasing returns to scale with respect to the accumulating factors of physical and human capital. Externalities and non-decreasing returns to scale are motivated by assumptions of knowledge being a pure public good with and without congestion problems see Barro, 1990, or knowledge being embodied in human capital. The *AK* model, for example, treats labour as another category of capital and allows it to accumulate over time. Arrow's (1962) 'learning-by-doing' model introduces a labour augmenting factor into the Solow-Swan model which increases as the economy invests and accumulates more capital. While firms face constant returns, the industry or economy as a whole faces increasing returns due to total "knowledge" in the economy. This knowledge and experience, Arrow argued, is common to all firms - a free and public good.

Further, Lucas (1988) suggests per capita production depends not only on how much physical and human capital a worker is equipped with, but also how much human capital is available in the whole economy (i.e., how much external human capital is available in the economy). To formulate this, Lucas assumes that the Solow shift parameter in the aggregate production function is a function of average human capital in the economy h_a , and the production per worker is $y = k^{\alpha} l^{1-\alpha} h_a^{\beta}$

where y is output per worker, k is capital stock per worker, and is effective labour of each worker.

One common characteristic shared among most models with endogenous growth from human capital, is to first treat all knowledge as an input into the aggregate production function and second allow the knowledge stock to accumulate over time. Human capital becomes cheaper to accumulate when its stock grows as in the process of learning a new idea, one also 'learns-to-learn' easier and subsequently help others to accumulate human capital more cheaply. This learning process is a constant source of positive externalities so that although knowledge production experiences diminishing returns at the firm level, at least constant and in some cases increasing returns exist at the aggregate level. That is:

$$Y = AK^{\alpha} L^{\beta}$$

$$\alpha + \beta = 1 \text{ or } < 1 \text{ (at firm level)}$$

$$\alpha + \beta = 1 \text{ or } > 1 \text{ (at aggregate level)} \qquad (2.5)$$

To empirically test this distinct characteristic of endogenous growth models requires detailed production data for each firm or at least for each industry in the economy, which is not easily accessible.

2.3 Endogenous Technological Change Models

In the endogenous growth model discussed above, technical progress would only be recognized when there are externalities extracted from the production function. However, in many situations the economic benefits of some new innovation exist in the *future* path of returns rather than in any gain on the *current* margin between old and new technology. Even with no immediate 'free lunches', no externalities or no super-normal profits on the investment of a new technology, the new technology could still open-up a set of opportunities that enables other technological discoveries through complementarities (see Carlaw and Lipsey (2002)).

There are a range of approaches that investigate this issue with implicit formulation of dynamism between technological changes and economic growth. One group of endogenous technological change models assumes that technology is unstructured, but that resources are endogenously allocated to bring-about technological change. Another growth of models assumes that technology has a structure, generally characterized by a prime mover technology such as a general purpose technology (GPT). Much of the dynamic process of technological change is modeled as the interaction between the GPT and its complementary technology (See Bresnahan and Trajtenberg (1996) for the seminal paper on GPTs).

A class of models that endogenise technological change assumes technology is unstructured and that firms do not act as price takers and imperfectly competitive firms allocate real resources to bring about changes in process technologies (See for examples, Grossman and Helpman (1991) and Aghion and Howitt (1992)). The incentive to innovate comes from the possibility to capture rent by innovating, which creatively destroys rents of rivals. Schumpeter (1934) first explained capitalist development as a process of “creative destruction,” in which entrepreneurs invest in innovations that aim to make the prior innovations of rivals obsolete and to extract monopoly rents. The monopoly rents will only be removed when further innovations are made by other entrepreneurs.

One possible approach to test this characteristic is to compare the total profits of two firms, which are selling close substitutes to each other for example, Microsoft and Apple. Apple was relatively large and earning supernormal profits before Microsoft developed Microsoft Windows. Testing for possible structural breaks or changing trend (upward) in Microsoft's total profits and noting whether the timing corresponds to the structural break and changing trend (downward) in Apple's total profits, might give us some empirical support for this particular characteristic of the endogenous growth model.

A second group of endogenous technological change models regard technology as having a hierarchical structure. Scientific innovations in those technological change models are sometimes identified as General Purpose Technologies (GPTs) such that "… economic growth is driven by a succession of GPTs, with opportunities for profitable investments in a large set of new products, processes, and organizational technologies... (Lipsey, Bekar & Carlaw 1998a)". The Structuralist Model of Lipsey, Bekar and Carlaw (1998b) and the general purpose technology models of endogenous growth of Carlaw and Lipsey (2001 and 2006) and Lipsey, Carlaw and Bekar (2005, chapter 14) provide methods of incorporating and measuring technological change in an endogenous growth model.

The two models by Helpman and Trajtenberg (1998) (H-T hereafter) suggest that an intermediate component which implements the new general purpose technology (GPT) requires some investment before it can be invented. New innovations would firstly cause a slump in the final output production before it creates a period of growth as a consequence of the shift of labour resource from the production of a final consumption good to the development of the intermediate component. Aghion and Howitt (1998) extended the H-T model by adding an additional 'social learning' stage and showed the slump does not necessarily occur immediately after the new GPTs arrive.

Riddell, Murphy & Romer (1998) construct an empirical testing approach in response to Aghion and Howitt (1998) that involves the growth rate of the gap between high and low educated work's marginal productivity $g(t)$ using a 'race model' of the wage premium $\frac{w_H}{w_l}$, and ratio of education attainment $\frac{H}{L}$:

$$g(t) = \frac{\delta}{\delta - 1}\{\frac{w_H}{w_L}(t) + \frac{1}{\delta}(\frac{H}{L}(t)) - c\} \quad (2.6)$$

H and *L* in the above equation denote university (high educated) and high school (low educated) labour, w_H and w_L are their wage accordingly. δ is the elasticity of substitution between *H* and *L* in the aggregate economy, and *c* is a constant. The study found in the US and Canada between 1970 and 1990, there were subperiods of slowdown and speed-up in the trend rate of growth of $g(t)$ (skill bias in technology), which correspond to the pattern of economic performance in the AH model.

2.3.1 Empirical tests of the relationship between ICT and economic growth in endogenous technological change models

If ICT is treated a major GPT that has arisen in recent years, we could test for possible structural breaks (or changing trends after correction for stationarity), in real GDP. If a structural break is shown to be significant then we could investigate whether the timing of the structural break corresponds to the arrival of ICT.

Potential problems with this approach are, that ICT is not the only GPT that has ever arrived or is currently in use in the economy, and there may be more than one structural break over the relevant time period. Furthermore, the exact timing of ICT arrival is hard to determine. As with all GPTs, ICT arrived in a crude form and required many complementary innovations that themselves were developed over several years and are continuing to be developed. The economic impact of this collection of innovation is not usually felt until well after such a GPT arrives (Lipsey et al 1998b).

Another approach, is to take the assumption of the endogenous technological change model that the "economy is driven by successive arrivals of new GPT" and examine whether a causal relationship works, i.e., ICT *causes* economic growth. However, caution is warranted because there is a complex interrelationship between what might be identified as the GPT and its complementary technologies, with the latter showing up across the entire spectrum of industrial sectors measured in the national accounts. This complexity is further compounded by the temporal lags that occur from the time a new GPT is introduced and the when a complementary technology may be developed and by the sometimes strong complementarities that exists between GPTs and related technologies. These strong complementarities preclude the attribution of marginal value to anyone technological component since the resulting integrated technology cannot exist in absence of either the GPT or its complementary technology.

2.4 The Technology Transfer Model (Cross-Country Convergence)

The neoclassical Solow growth model assumes technology to be a free good available across countries without adoption costs. Under this assumption, all countries will in the long-run converge to the same steady state per capita growth, that is, the rate of technological progress, *g*. The empirical evidence, in contrast, typically suggests a significant disparity in the growth rates across countries (Islam 2003), with the leaders being the US and the OECD countries, followed by the rapid postwar growth in Japan. A small cluster of Asian countries Korea, Taiwan, China, and Singapore have also shown strong upward trends in their economic growth in the recent years. However, the third world countries remain behind in the low income growth groups. The Mankiw, Romer and Weil (1992) (MRW) approach based on neoclassical growth theory explains such a discrepancy in international growth rate as purely the "transitional dynamic" which will eventually disappear when countries converge to their steady state equilibrium.

In contrast, there is a view that identifies the 'technology-gap' or the problem of 'cross country convergence' as the culprit. These views propose that technology is not freely accessible for all countries, and could indeed widen the income gap. The endogenous growth models of Romer (1986), Lucas (1988), and Scott (1989) suggest that new investment would lead to technological progress in the form of 'learning-by-doing.' which enables capital stocks to have increasing returns to scale at the aggregate level. The marginal productivity of capital does not diminish with increasing GDP per capita, and the wealthy countries will continue to grow and its GDP per capita will remain above the less well-endowed countries.

Bernard and Jones (1996) take a slightly different approach to explaining the difference in cross country growth rates by calling for further research on technology transfer as an explanation of convergence. Their work starts from a simple Solow growth model and incorporates technology transfer in the form of:

$$\frac{\dot{A}_i}{A_i} = \xi_i \left(\frac{A_w}{A_i} \right) \tag{2.7}$$

where ξ_i indexes the ability of a country to adopt the most productive labour augmenting technology, A_w, which is assumed to grow exogenously. The steady state technology ratios are given by:

$$\frac{A_i}{A_w} = \frac{\xi_i}{\xi_w} \tag{2.8}$$

Thus in contrast to Solow, which claims the steady state growth rates from output per capita and the capital labour ratio for each country will equal the growth of the world's labour-augmenting technology, the steady state level of output per capita in this framework depends not only on the aggregate factors, but also on the ability of countries to adopt the frontier level of technology:

$$\frac{y_i^*(t)}{y_{us}^*(t)} = \frac{\xi_i}{\xi_{us}} \cdot \frac{\left(\frac{s_i}{n_i + g + \delta_i}\right)^{\alpha_i/(1-\alpha_i)}}{\left(\frac{s_{us}}{n_{us} + g + \delta_{us}}\right)^{\alpha_{us}/(1-\alpha_{us})}} \tag{2.9}$$

where subscript '*US*' denotes the country (the US) that they assume to be the technology frontier country, and '*i*' represents any other countries. n, g, δ indicate the relative savings rates, depreciation rates, and population growth rates. The implication here is that the technology transfer rate determines how fast a country converges to other advanced countries. If two countries' growth rates converge, the difference in adoption of technologies would also tend to equal zero. Bernard and Jones (1996) is one of the first technology transfer models and motivates much subsequent research in this area, for example Dowrick and Rogers (2001) and Castellacci (2001).

2.4.1 How might the technology transfer model be tested?

One approach to test the technology transfer model, based on Bernard and Jones (1996), is to investigate how the difference in the pattern of adoption rates of the particular technology, ICT, affects how growth rates converge between countries. We treat the US as the 'benchmark country' and test the correlation between the difference in growth rate and the difference in the ICT variables between each country and US. The Solow growth model is used as the null, which implies the slope parameter, β, from equation (2.10) is not statistically different from zero, with the alternative hypothesis of β being statistically greater than zero that supports the technology transfer model. Thus we have the test equation of:

$$\left(g_t^{US} - g_{t^i}^{i}\right) = \alpha + \beta\left(\frac{Total\ ICT\ spending_{t-j}^{US}}{real\ GDP_{t-j}^{US}} - \frac{Total\ ICT\ spending_{t-j}^{i}}{real\ GDP_{t-j}^{i}}\right) + \varepsilon_t \qquad (2.10)$$

An alternative approach is to divide the world into three groups, developed, developing, and less-developed countries, and see how the correlation varies across groups instead of from one country to another.

In summary, the technology transfer models in this subsection, the Solow, endogenous, and endogenous technological progress models, all support the proposition that technology has a significant role in the determination of economic growth or cross country growth convergence. Lipsey, Carlaw and Bekar (2005) argue first that technology has structure, second that transforming technologies called ‘general purpose technologies’ impact the economy over many years even centuries, and third that some GPTs that require significant structural change and many complementary innovations have a diffusion pattern that is either not correlated or negatively correlated with TFP growth.They also argue that TFP is not a measure of technological change. Carlaw and Oxley (2004) and Carlaw (2004) provide evidence for New Zealand and Australia that loosely supports the theoretical prediction of Lipsey, Carlaw, and Bekar (2005).

In Section 4 we will present a summary of results from recent empirical studies which directly or indirectly consider the role of technology (ICT) in the growth process. In the next section we will consider what data is available to test such relationships and which has been used in the range of studies undertaken.

3.0 Available Data Sources

A review of data sources reveals that an inclusive and consistent cross-country measure of ICT is not available and likewise consistent and comparable cross-country data. This Section provides a summary of data sets used by recent studies and is summarized as Table 3.1 below[11].

For cross-country ICT expenditure data, the most commonly used and complete data set is the *Digital Planet* published by *The World Information Technology and Services Alliance* (WITSA). WITSA data are collected and compiled by the International Data Corporation (IDC[12]), and cover a wider range of countries, including some less-developed economies. Daveri (2001) claims '…this (*Digital Planet*) is the only source of consistent information technology data for a large cross-section of countries in the 1990s…' It is important to note that the ICT spending of unincorporated enterprises are excluded by WITSA. Furthermore, appropriate price deflators for ICT commodities do not exist for most EU countries, let alone for the rest of the countries included in the publication, however, the European Information Technology Observatory (EITO[13]) is a useful source of relevant data.

<u>Table 3.1 near here</u>

Colecchia and Schreyer (2001) provide ICT investment data for nine OECD countries, using recent published official data in each country and a set of 'harmonized' deflators from Schreyer (2000) to overcome some of the differences in measurement methodologies between countries. Other studies, however, estimate the investment data by multiplying the estimated percentage of investment from total spending by the corresponding total spending. For example, one common method is to use the BEA investment and total spending ratio, multiplied by the corresponding WITSA spending items for EU countries to derive nominal ICT investment spending data, (Vijselaar and Albers 2002, Goldman and Sachs 2000, Daveri 2001). For investment data prior to 1992, where WITSA data does not exist, OECD and World Bank data on ICT import shares can be used as an alternative to back-project (Caselli and Coleman 2001, Daveri 2001).

At the micro-firm level the OECD STructural ANalysis (STAN)[14] Industry Database and the Groningen Growth and Development Center (GGDC[15]) provide economy-wide and 60 industry databases and are used in a series of papers by, in particular, van Ark and co-authors.

For information on global Internet access, the *Nua Internet Survey*[16] provides exclusive data from 1992. General information on the number of ICT infrastructures including PCs, telephones, faxes etc., in each country for the last 5-10 years can be found from organizations including the OECD, World Bank and International Telecommunication Union (ITU[17]). The ITU in particular, provides extensive data on global telecommunication facilities from 1975 to 2001.

4.0 Empirical Results: A Review[18]

Section 2 summarized four types of economic growth model and testing frameworks. In this Section we consider whether current empirical results support any of these models. A review of empirical results from the growth accounting framework will be presented in subsection 4.1, followed by empirical results from other approaches in 4.2[19].

4.1. Empirical Results from a Growth Accounting Approach

The growth accounting approach is probably the most common approach to testing the impact of ICT on economic growth. Solow (1956) uses aggregate US data 1900-49 with output growth 2.75%, capital and labour share growth of 1.75% and 1.00% respectively such that with constant return to scales[20], TFP is calculated as:

$$TFP = \frac{\dot{Y}}{Y} - \alpha \frac{\dot{K}}{K} - \beta \frac{\dot{L}}{L}$$

$$= 2.75\% - (0.35)*1.75\% - (0.65)*1.00\%$$

$$=1.49\%$$

Many studies use the growth accounting approach to examine ICT's *contribution to output growth, labour productivity growth and TFP* and do not require extensive time series data.

4.1.1. Results for the US

Most of the growth accounting research, reported in Table 4.1 below, relate to the US either as the primary/sole focus or more typically as a benchmark to compare against the performance of other countries. Here, researchers generally found acceleration in the annual GDP growth, labour productivity growth and TFP growth in the US data during the 1990s, especially in the second half of that decade. Using this approach, the authors calculate the contribution of ICT capital to be anywhere between 13% (Lee and Khatri 2003, for 1990-94) and 38% (Colecchia and Schreyer, 2001, for 1995-2000) of the US annual GDP growth. ICT capital contributes between 20% (Goldman Sachs, 2000, for 1990-95) to 38% (Timmer et al., 2003 and US Council of Economic Advisors, 2001 for 1995-2001 and 1995-2000 respectively) of the US annual labour productivity growth. According to these studies, the contribution of TFP in ICT production also accounts for a significant proportion of annual labour productivity growth. Gordon (2000), Goldman Sachs (2000) and Jorgenson and Stiroh (2000) calculate that between 21%-30% of labour productivity growth between 1995-2000 was attributable to TFP in ICT industries. The US Council of Economic Advisors see this being closer to 38% (1995-2000) and Timmer *et al*. (2003) calculate the contribution to be 44% for the period 1995-2001.

(Table 4.1 near here)

4.1.2. Results for the European Union

The story is slightly different for the European Union. ICT capital contributes between 6-23 % of EU output growth in the period 1990-2000 (van Ark, 2002). These figures are supported by the European Central Bank (ECB), (2001) where Euroland shows a contribution range of between 15-22 % for the period 1990-1999. The results from other authors for example, Daveri (2001, 2002) Colecchia and Schreyer (2001) and Timmer *et al.* (2003) confirm these broad parameters, but with particular country specific highs and lows. Although the contribution of ICT has increased since the 1980s, it is still much less than the US (ECB, 2001).

Since 1995, EU labour productivity growth and TFP growth appears to have slowed except in Ireland and Greece, but the relative contribution of ICT as a percentage of aggregate labour productivity growth in the EU has been similar to the US. In absolute terms, the percentage point contributions of ICT capital to labour productivity growth have doubled in the US, but only increased by 50 % in the EU. In the 1990s, the contribution to TFP from ICT production doubled in the EU, but tripled in the US (van Ark, 2002a). A summary of a number of studies' estimates of ICT capital's contribution to annual labour productivity, GDP growth, and the contribution of total factor productivity in ICT production to annual labour productivity growth, in a range of countries, is presented as Table 4.1.

Within the European countries, there is also varying evidence on the contribution of ICT to output growth, labour and total factor productivity (Daveri, 2002, van Ark, 2002a). The UK, Italy, Germany and Netherlands have a high *relative* contribution of ICT capital, on average 16.45 %, to the growth in real GDP in 1995-2000, close to the US at 16.7 %. Ireland, Portugal, Finland and Spain on the other hand, each has less than 8 % of output growth, and are the four countries with the lowest ICT capital share of real GDP growth. In terms of the *absolute* contribution to labour productivity growth, Ireland is the only country in the EU which has a higher ICT capital share of labour productivity than the US (Ireland 0.6511, US 0.615), followed by the UK, 0.5029 and Netherlands, 0.46113 see Figure 4.1.1 below, from van Ark 2002a. The European Union cluster overall have a lower percentage share of ICT production to TFP than the US, individual countries including, Ireland, Finland, Austria, Portugal and Sweden though, achieve higher ICT production share to total TFP.

(Figure 4.1: near here)

The OECD countries experienced increased labour productivity growth and TFP growth between 1990-95 and 1995-2000 (Goldman Sachs 2000). ICT capital in the OECD countries was apparently responsible for 0.38% of the 1.8% increase in Annual Labour Productivity (ALP) growth, 1990-95 and 0.73 of the 2.1% in 1995-2000. The ICT industry’s contribution to TFP growth has also grown from 21.6% to 30.0% from the first half of 1990s to the second half (Goldman Sachs 2000).

4.1.3. Results for other country groupings

4.1.3.1 Asia

Rapid ICT growth has also taken place in some newly industrialized Asian countries, but few growth accounting studies have been undertaken for them. Japan as part of the G7 has ICT capital accounting for 0.19% of 1.8% output growth (Schreyer 2000), 0.820% of 1.55% ALP growth, and 0.345% of the 1.55% TFP growth, in line with West Germany (Goldman Sachs 2000). South Korea's ICT direct contribution is 10.7% to value added in the business sector in 1997 which is ahead of all other OECD countries in that year. Wong (2001) suggests that the GDP share of ICT goods and services was over 14% in Singapore in the mid 1990s and the production of ICT goods accounted for 12% of economic growth in 1970-75. Lee and Khatri (2003) calculate that the contribution of ICT to GDP range from 55% (Hong Kong), 1995-1999 to 1.7% for India (1995-1999). Much less is known of the contribution of ICT to labour productivity or to TFP in these studies.

4.1.3.2 Transition Economies

There are few empirical results using the growth accounting approach for areas outside the OECD and newly industrialized Asian countries, the exceptions being a group of papers examining the impact of ICT on growth in the transition economies, of Hungary, Slovakia, Slovenia, Poland, Bulgaria, Romania, Russia and the Czech Republic see for example, Piatkowski (2003, 2004), and van Ark and Piatkowski (2004). Their work suggest that between 8% (Russia) and 32% (Czech Republic) of GDP growth was attributed to ICT over the period 1995-2001. On the contribution of ICT to labour productivity growth, the relevant ranges as measured by van Ark and Piatkowski (2004) are 12% (Slovakia) to 26% (Bulgaria). Finally, on the contribution of TFP in ICT to ALP growth, the relevant ranges, from the same authors, are 21% (Czech Republic) to 66% (Slovenia).

4.2. Other Types of Empirical Study

In addition to the growth accounting approach, a number of other methods have been used to examine the relationship between ICT and growth. In this subsection, we summarize a selection and present a summary of the results as Table 4.2 and consider details in the text.

One of the simplest approaches to examine the short run relationship between two variables is *correlation analysis*. Empirical results generally find significant correlation between ICT and economic growth. For example, Kraemer and Dedrick (2001) found average annual growth in investment in information technology significantly correlates with average annual GDP and productivity growth in twelve Asia-Pacific countries in 1984-90 at the 0.05 and 0.01 levels respectively. They suggest countries with higher growth rates in IT investment would persistently achieve higher productivity growth and subsequently higher growth of GDP.

Several studies use OLS-based *regression analysis*. Quibria (2002) and Kiiski & Pohjola (2002) used ICT as the dependent variable and found national income/per capita had a significant effect on ICT infrastructures/diffusion.

(Table 4.2 near here)

Several studies apply OLS to the log form Cobb-Douglas production function and test the impact of ICT investment on domestic output. These studies generally provide mixed results suggesting ICT does not always lead to greater growth. Dewan and

Kraemer (2002) found IT investment induced higher output in developed countries, but not developing countries. Pohjola found the impact of IT investment on growth changing from significant to insignificant when the sample size changes from 39 countries in 1980-95 to 42 countries, 1985-99 (Pohjola 2001, 2002). When the scope is narrowed to firm level empirical studies, the results are also mixed. Gurbaxani, Melville and Kraemer (2001) found that investment in mainframe PCs has a positive return to production, whereas Gurbaxani, Gilchrist and Town (2001) conducted GMM[21] estimation and found IT investment affects productivity in durable goods sectors, but not in the non-durable sectors.

Moving from short run analysis to long run analysis, some researchers adopt a *causality testing framework* to examine the significance of uni/bidirectional causal relationships between two variables. In contrast to Pearson Correlation and OLS, results from causality analyses give little evidence supporting ICT and economic growth. This is probably due to the lack of long time series ICT data across countries. Lee and Gholami (2002) constructed Granger causality tests between IT investment and economic growth for 16 countries, 1970-99. They found no causal relationship from IT to GDP except for Denmark, Italy, US and UK. Even among those four countries, the F test statistics are significant only at the 10% level. Lee and Alba (2001) used the Geweke causality test to examine the relationship between R&D expenditure for twelve OECD countries and Taiwan in both sectoral and aggregate level. They found bidirectional causation from growth of R&D expenditure to growth of output in the manufacturing sector in only five out of twelve OECD countries. For aggregate level analyses, they found bidirectional causation is significant in France and Italy, and unidirectional relationships from R&D expenditure per capita growth are significant in South Korea and Taiwan.

As a number of studies found mixed results for short run and long run relationship between ICT and growth, some researchers turned to testing ICT's impact on *cross-country convergence*. The 'technology transfer models' suggest countries with a greater ability to adopt technology from the leading countries enjoy higher growth. The empirical studies generally show similar results to this hypothesis. Bernard and Jones (1996) found the change in the dispersion of labour productivity over the period 1970-1988 corresponds closely with the change in the dispersion of technology in the OECD countries. Hollanders, and ter Weel (2002) also constructed analysis for the OECD that used a "catch-up" model and found countries with relatively low productivity levels can reduce the gap using knowledge spillovers from advanced countries for the period 1991-7.

There are few empirical studies of ICT's direct impact on growth convergence, which is probably due to the unavailability of complete cross country ICT data. Lee, Oh, and Seo (2002) used a catch-up model and found the disparity in IT investment increases the differences in the economic growth among OECD countries, 1991-97. Their results show countries which make rapid progress in IT capital formulation, experience higher labour productivity growth, and consequently higher output growth than the average OECD member countries.

Finally, there is alternative approach, developed in response to the endogenous technological growth model that tests the significance of ICT on the economy through its *impact on income distribution,* i.e. the wage premium of high skilled labour and low skilled labour. Murphy, Riddell and Romer (1998) test the correlation between the trend rate of growth of skill bias in technology $g(t)$ over time with the pattern of economic performance and found the two significantly correlated. Other studies use dummy variables for 'ability to use PCs, mainframe, fax etc' on the wage rate.

Morissette and Drolet (1998) found male computer users in Canada generally earn 6-14% more than non-users whereas for women, the computer use wage premium either is not significant or reaches a maximum of 11%. Male fax users earn 11-20% more than non-users and women fax users wage premia varies between 13% and 19%. Bruinshoodf and ter Weel (1998) found a positive correlation between the R&D intensity of a sector and the relative wage rate of white-collar to blue-collar to be increasing in Netherlands over the 1990s. Likewise, the wage rate of high skilled workers relative to low skilled workers increases with the degree of R&D intensity, suggesting wage divergence is stronger in technologically advanced sectors relative to technologically less-advanced sectors.

4.3 Summary of empirical results: Support for theoretical models

Section 2 outlined a range of theories which have a particular role for technological change in the economic growth process and importantly identified a range of testable hypotheses which might help distinguish which, if any, had empirical support in relation to ICT as the new technology. The results presented as Section 4 list what has been reported in respect of actual empirical results. Not all map directly into the type of hypotheses identified via Section 2, but many do. So, what do the results suggest about support for the four broad categories of distinguishing testable hypotheses?

The growth accounting framework is the main tool used to test the implications of the **Solow growth model** which involves examination of ICT's *contribution to output growth, labour productivity growth and TFP. In general the results contradict the implications of the Solow growth model*. With the adoption of ICT being recognized as some form of technological progress, significant increases in the proportion of ICT in national production does not always lead to significant increases in final output. Although ICT and economic growth are typically correlated see Kraemer and Dendrick (2001) and significant in an OLS regression (Quibria 2002 and Kiiski and Pohojla 2002), these authors also conclude that ICT does not always lead to greater growth. When causality testing is used, little evidence is found of ICT causing growth except in the case of Denmark, Italy, US and UK, see Lee and Gholami (2002). Many EU countries, in fact, experienced a slowdown in economic growth in the last two decades namely the 'Productivity Paradox' or the 'Solow Paradox,' where Solow states '…you can see computers everywhere, but in the productivity statistics… (Solow 1987).' This could result, in practice, from slow diffusion of technological change. However, slow diffusion is not a characteristic of a neoclassical world of instantaneous adoption and hence not an appropriate explanation within this paradigm of the observed 'slowdowns'.

Rigorous tests of what we have called a the **endogenous growth model with no explicit technological change** applied to ICT data do not appear to exist in the literature most likely because of the extreme data requirements imposed on the class of hypotheses.

The **endogenous growth model with explicit endogenous technical change approach** finds some empirical support in the work of Murphy, Riddell, and Romer (1998) which operates via implications on wage gaps. However, we identified the importance of timing issues, structural breaks and causal relationships between new technology (ICT) arrivals and economic growth. The only evidence here would be weakly negative, based upon the lack of evidence of a significant causal relationship between ICT and economic growth.

Support for the **technology transfer model** *(cross country convergence)* seems to be somewhat stronger for example Hollanders, and ter Weel (2002) found countries with relatively low productivity levels can reduce the gap using knowledge spillovers from advanced countries for the period 1991-7. Lee, Oh, and Seo (2002) show that countries which make rapid progress in IT capital formulation, experience higher labour productivity growth, and consequently higher output growth than the average OECD member countries.

5.0 Conclusions

Few would argue with at least part of Solow's classic 1987 observation, "you see computers everywhere", however, their role and impact as an engine of economic growth is a controversial question. In order to address such a broad question we have presented, as Section 2, a range of theoretical models which show a role for ICTs in economic development and importantly their testable implications. Section 4 presented a survey of much of the empirical literature attempting to identify which theoretical models/approaches the results might support/refute.

ICT and economic performance are clearly correlated, but so are many economic time series, if only spuriously. The issue of causality which is key to (and distinguishes) several of the modeling approaches, is currently confounded by the lack of appropriate, timely and extended data series. However, the framework we have presented here identifies a number of direct and indirect testable hypotheses that may be used to accumulate evidence to make a case for one approach (and its economic and policy implications) over another. Evidence on slow and varied diffusion of new technology seems to indicate that the instantaneous and free adoption of new technology within the Solow model appears not to be the way to model. Does it make any difference? The clearest difference would be in relation to policy implications and therefore the attempts by many agencies to link TFP and productivity measures to *current valued* GDP statistics. ICT may have profound, significant and large effects on economic performance, but TFP probably does not measure technology well and even if it did, investment in new technology is unlikely to generate *instantaneous* positive responses. The likely short-term effects of ICT development and investment are more likely to involve reductions in economic growth (in the first instance) until the technology is in place and diffused.

In conclusion we would encourage more research in this area with the caveat that it should be via a richer research agenda. The growth accounting approach seems to tell us as much as we need to know, at present, about the average contribution of various sectors to economic performance. It is easy to use, however as a methodological approach, it is constrained by the use of a neoclassical production function with its underpinnings and constraints. The *key issue* in empirical testing would seem to be data availability. Until time passes (and it is not an issue that panel data can resolve as the time dimension is crucial) the jury may remain out. However some researchers (Carlaw (2004) have provided theoretical and simulation-based critiques of the Solow approach and Solow Paradox which may contribute to the final answer on the role of ICT in economic development.

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Appendix 1

The fifty-five countries included in WITSA's *Digital Planet* are:

Argentina	Australia	Austria	Belgium	Brazil
Bulgaria	Canada	Chile	China (PRC)	Colombia
Czech Republic	Denmark	Egypt	Finland	France
Germany	Greece	Hong Kong	Hungary	India
Indonesia	Ireland	Israel	Italy	Japan
Korea	Malaysia	Mexico	Netherlands	New Zealand
Other Asia Pacific	Other Eastern Europe	Other Latin America	Other Middle East/Africa	Saudi Arabia/ Gulf States
Norway	Philippines	Poland	Portugal	Romania

Appendix 2

The Solow- Swan Growth Model

The Solow (1956) framework assumes a closed country in a continuous time world without technical progress. Two types of agents exist in the economy, households and a single firm where the number of households is size *N* at time *t* and grows at rate *n*. There is only one output *Y*. Each household spends *C* from their labour income and saves the remainder. The capital stock is the only asset available in the economy, and thus saving from the households is equivalent to the level of investment in capital goods. Capital depreciates at rate δ and $0 < \delta < 1$. With the marginal propensity to save being *s*, the capital stock, *K* at time *t* is :

$$\dot{K} = sY - \delta K \qquad \text{(A1)}$$

The production function of output *Y* (A2) is assumed to have the properties identified by (A3) – (A5)

$$Y = F(L, K) \qquad \text{(A2)}$$

$$0 = F(0,0) \qquad \text{(A3)}$$

$$aY = F(aL, aK) \qquad \text{(A4)}$$

$$F_L, F_K > 0 \quad F_{LL}, F_{KK} < 0 \qquad \text{(A5)}$$

Per capita production *y* (*Y/N*) as a concave function of the capital-labour ratio *k* (*K/N*):

$$y = f(k) \qquad y_k > 0, \quad y_{kk} < 0 \qquad \text{(A6)}$$

The Solow model provides a unique steady state equilibrium where there exists a level of capital-labour ratio, *k**, which generates sufficient saving to maintain the level of investment that is necessary to sustain the current capital-labour ratio. The rate of change of the capital-labour ratio, *k*, at a given time is:

$$\dot{k} = sf(k) - (n + \delta)k \qquad \text{(A7)}$$

Extending the Solow framework to include exogenous technical progress most researchers assume *neutral* technical change where the MRTS[22] changes in a specific and uniform manner, i.e.,*Harrod-neutrality* where the MRTS changes proportionately in favor of labour for all input vectors in a form of labour-augmenting production function:

$$Y = F(AL, K) \tag{A8}$$

Technical progress proceeds at a constant rate, *g*[23]

$$\frac{\dot{A}}{A} = g \tag{A9}$$

Rewriting as output per effective unit of labour $\tilde{y}$ in terms of capital per effective labour $\tilde{k}$.

$$\tilde{y} = f(\tilde{k}) \text{ where } \tilde{y} = Y / AL \text{ and } \tilde{k} = K / AL$$

The rate of change of the capital-effective labour ratio is:

$$\dot{\tilde{k}} = sf(\tilde{k}) - (n + g + \delta)\tilde{k} \tag{A10}$$

In contrast to before, growth of output per capita does not falls to zero, instead it continues to grow at the constant rate, *g*.

Figure 4.1: data source: van Ark 2002

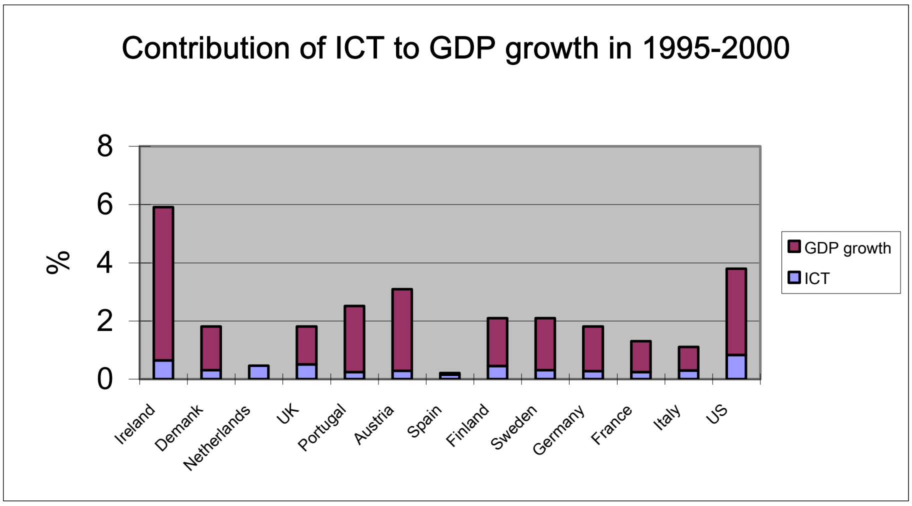

Table 3.1 Data sets used in some recent studies

Author	Country and Time Coverage	Data	Source of Data	Use of data
Bassanini & Scarpetta (2002)	OECD 1980-2000	ICT spending	OECD	Growth Accounting
Bruinshoodf & Ter Weel (1998)	Netherlands, 1992 &1996	Wage rates in diff. industries	STAN[24]	OLS
Daveri (2000)	Europe, US 1990s	IT investment, capital, spending	WITSA[25], OECD, Schreyer (2000), Stiroh (2000), Oliner & Sichel (2000)	Growth Accounting
Daveri (2002)	Europe 1992-2002	ICT spending & investment	IDC[26]	Growth Accounting
Daveri (2003)	G7 countries 1990s	IT spending, investment	WITSA, OECD, Van Ark (2002)	Growth Accounting
Goldman Sachs (2000)	OECD, US, Japan, UK, Euroland 1990-99	ICT output, investment	OECD	Growth Accounting
Gordon (2002)	US, 1990s	IT diffusion, IT goods and services	BEA[27]	Growth Accounting
Gurbaxani, Melville & Kraemer (2001)	US, firm level data 1987-94	No. mainframes, minicomputers, microcomputers	IDC	OLS on Augmented Cobb-Douglas
Gurbaxani &Town (2001)	US, firm level data 1986-93	IT investment	CII[28]	GMM on Augmented Cobb-Douglas
Inklaar et al. (2003)	EU and US, 1990s	ICT output (incl. industry level), investment	OECD STAN, (National Institute for Economic and Social Research) NIESR and GGDC	Growth Accounting
Jorgenson (2001)	US 1990-99	ICT output, investment	BEA	Growth Accounting

Kiiski & Pohjola (2001)	OECD Countries and countries with more than 50 Internet hosts 1995-2000	Internet access costs and growth of computer hosts per capita	Internet Host domain survey (by Network Wizards)	OLS
Kraemer & Dedrick (2001)	12 Asia Pacific countries 1984-1990	IT Investment	Confidential Industry Source	Pearson Correlation
Lee and Gholami (2002)	16 countries, 1970-99	IT investment	OECD:STAN and UNIDO[29]	Granger Causality
Lee and Khatri (2003)	Asian countries and US, 1990s	ICT output, investment	WITSA/IDC, BEA and BLS	Growth Accounting
Lee, Oh, Seo (2002)	Seventeen OECD countries, 1991-7	IT investment	OECD	OLS on Catch-up Models
Morissette & Drolet (1998)	Canada, 1994	Wage rates for PC/Fax and non-PC/Fax users	GSS[30]	OLS
Neo & Alba (2001)	14 countries, 1967-93	R&D expenditure	OECD:STAN	Geweke Causality
Oliner and Sichel (2000)	US 1991-99	ICT output, investment	BEA	Growth Accounting
Oulton (2000)	UK 1980-2000	ICT output, investment	ONS[31]	Growth Accounting
Pohjola (2002)	42 countries 1985-99	ICT Investment and Spending	WITSA, Penn World Tables	OLS on Augmented Cobb-Douglas
Quibria (2002)	100 Countries 1992-2002	ICT Infrastructures	ITU[32], Nua Internet Surveys	OLS
Schreyer (2000)	7 OECD countries 1990-96	ICT output, investment	OECD	Growth Accounting
Colecchia & Schreyer (2001)	9 OECD countries 1990-99	ICT output, investment	OECD	Growth Accounting
van Ark (2002)	OECD 1980-2000	ICT output, investment	OECD, WITSA local government officials, and various empirical studies	Growth Accounting
van Ark and Piatkowski (2004)	EU-15, EU-25, Central & Eastern Europe), CEE-10, and US, 1990s	ICT output (incl. industry level), investment	OECD STAN and GGDC[33] 60 industry database	Growth Accounting

Table 4.1 Summary results of representative Growth Accounting studies

Author	Country and Time Coverage	Contribution of ICT Capital to		Contribution of TFP in ICT production to ALP Growth
		Annual GDP Growth	ALP[34] Growth	
van Ark & Piatkowski (2004)	Slovakia 1995-2001		0.6 out of 4.8	2.8 out of 4.8
	Poland 1995-2001		0.6 out of 4.4	2.1 out of 4.4
	Slovenia 1995-2001		0.5 out of 3.8	2.5 out of 3.8
	Romania 1995-2001		0.3 out of 3.5	1.8 out of 3.5
	Hungary 1995-2001		0.7 out of 3.3	2.4 out of 3.3
	Czech Rep 1995-2001		0.8 out of 2.8	0.6 out of 2.8
	Bulgaria1995-2001		0.5 out of 1.9	1.6 out of 1.9
van Ark (2002)	Austria 1990-95	8.6%	0.16 out of 1.7	
	1995-00	10.6%	0.29 out of 3.1	
	Denmark 1990-95	8.1%	0.18 out of 2.51	
	1995-00	11.5%	0.31 out of 1.81	
	Finland 1990-95	-10.2%	0.15 out of 2.31	
	1995-00	6.1%	0.28 out of 3.31	
	France 1990-95	15.4%	0.16 out of 1.41	
	1995-00	10.5%	0.24 out of 1.31	
	Germany 1990-95	16.5%	0.27 out of 2.91	
	1995-00	15.5%	0.27 out of 1.81	
	Ireland 1990-95	4.2%	0.17 out of 3.61	
	1995-00	8.0%	0.65 out of 5.91	
	Italy 1990-95	16.1%	0.24 out of 3.01	
	1995-00	16.5%	0.30 out of 1.11	
	Netherlands 1990-95	13.5%	0.25 out of 1.11	
	1995-00	15.3%	0.46 out of 0.41	
	Portugal 1990-95	9.7%	0.20 out of 3.51	
	1995-00	7.0%	0.24 out of 2.51	
	Spain 1990-95	10.7%	0.16 out of 2.31	
	1995-00	6.1%	0.15 out of 0.21	
	Sweden1990-95	22.7%	0.14 out of 1.91	
	1995-00	11.5%	0.31 out of 2.10	
	UK 1990-95	13.5%	0.25 out of 2.71	
	1995-00	18.5%	0.50 out of 1.81	
	EU 1990-95	16.2%		
	1995-00	15.5%		
	US 1980-85	14.7%		
	1985-90	16.7%		
Cette et al (2000)	France 1989-95	0.17		
	1995-99	0.27		
Crepon and Heckel (2002)	France 1987-98	0.32		
Daveri (2001)	Ireland 1991-99	0.64 out of 6.9		
	Denmark 1991-99	0.52 out of 2.9		
	Netherlands 1991-99	0.68 out of 2.8		
	UK 1991-99	0.76 out of 2.7		
	Portugal 1991-99	0.43 out of 2.5		
	Austria 1991-99	0.45 out of 2.3		
	Spain 1991-99	0.36 out of 2.3		
	Greece 1991-99	0.34 out of 2.3		
	Finland 1991-99	0.45 out of 2.1		
	Belgium 1991-99	0.48 out of 1.9		
	Sweden 1991-99	0.50 out of 1.9		
	Germany 1991-99	0.49 out of 1.7		
	France 1991-99	0.41 out of 1.6		
	Italy 1991-99	0.31 out of 1.4		

Daveri (2002)	US 1996-99 UK 1996-99 Sweden 1996-99 Spain 1996-99 Portugal 1996-99 Netherlands 1996-99 Italy 1996-99 Ireland 1996-99 Greece 1996-99 Germany 1996-99 France 1996-99 Finland 1996-99 Denmark 1996-99 Belgium 1996-99 Austria 1996-99	1.45 1.17 0.85 0.34 0.49 0.72 0.35 0.96 0.46 0.45 0.44 0.74 0.65 0.49 0.43		
Daveri (2003)	USA 1990-95 USA 1995-00 France 1990-95 France 1995-00 Germany 1990-95 Germany 1995-00 Italy 1990-95 Italy 1995-00 UK 1990-95 UK 1995-00		0.3 of 1.2 0.6 of 2.2 0.16 of 1.38 0.24 of 1.35 0.27 of 2.90 0.27 of 1.80 0.24 of 3.00 0.30 of 1.13 0.25 of 2.70 0.50 of 1.80	0.7 of 1.2 1.39 of 2.2 0.48 of 1.38 0.89 of 1.35 1.73 of 2.90 1.14 of 1.80 1.96 of 3.00 0.46 of 1.13 1.88 of 2.70 0.84 of 1.80
European Central Bank (ECB) (2001)	Euroland 1990-95 1996-99	0.22 out of 1.5 0.42 out of 1.9	0.26 out of 2.4 0.39 out of 1.3	
European Commission (2000)	EU 1991-95 1995-99		0.2-0.3 out of 2.0 0.3-0.5 out of 1.5	1.0 out of 2.0 0.2 out of 1.5
Goldman Sachs (2000)	OECD 1990-95 1996-99 US 1990-95 1996-99 Japan 1990-95 1996-99 UK 1990-95 1996-99 Euroland 1990-95 1996-99		0.38 our of 1.8 0.73 out of 2.1 0.35 out of 1.7 0.79 out of 2.7 0.55 out of 1.2 1.14 out of 1.9 0.37 out of 3.4 0.84 out of 1.8 0.28 out of 2.1 0.38 out of 1.4	0.39 out of 1.8 0.63 out of 2.1 0.41 out of 1.7 0.83 out of 2.7 0.48 out of 1.2 0.55 out of 1.9 0.22 out of 3.4 0.40 out of 1.8 0.33 out of 2.1 0.69 out of 1.4
Gordon (2000)	US, 1995-1999			0.29 out of 1.33
Jalava and Pohjola (2001)	Finland 1990-95 1995-99	0.3 out of -0.3 0.7 out of 5.6	0.5 out of 4.4 0.6 out of 3.2	0.7 out of 4.4 1.2 out of 3.2
Jorgenson (2001)	US 1991-95 1996-99		0.43 out of 1.2 0.89 out of 2.1	0.25 out of 1.2 0.5 out of 2.1
Jorgenson & Stiroh (2000)	US, 1995-1998		0.34 out of 0.95	0.24 out of 0.95

Lee and Khatri (2003)	US, 1990-94 1995-99 Hong-Kong, 1990-94 1995-99 Indonesia, 1990-94 1995-99 Korea, 1990-94 1995-99 Malaysia, 1990-94 1995-99 Philippines, 1990-94 1995-99 Singapore, 1990-94 1995-99 Taiwan, 1990-94 1995-99 Thailand, 1990-94 1995-99 India, 1990-94 1995-99 China, 1990-94 1995-99	0.26 our of 2.01 0.78 out of 3.63 0.86 out of 5.02 1.17 out of 2.10 0.15 out of 8.51 0.19 out of 1.26 0.90 out of 7.96 1.10 out of 5.90 0.42 out of 9.36 0.56 out of 5.12 0.18 out of 2.72 0.31 out of 4.96 0.94 out of 8.75 1.36 out of 5.59 0.40 out of 6.97 0.58 out of 6.46 0.22 out of 9.59 0.22 out of 1.89 0.06 out of 5.22 0.11 out of 6.56 0.14 out of 10.63 0.27 out of 8.76		
Oliner and Sichel (2000)	US 1991-95 1996-99	0.57 out of 2.8 1.10 out of 4.8	0.51 out of 1.5 0.96 out of 2.6	
Oulton (2001)	UK 1989-94 1994-98		0.39 out of 2.6 0.62 out of 1.6	
Piatkowski (2004)	Slovakia 1995-2001 Poland 1995-2001 Slovenia 1995-2001 Romania 1995-2001 Hungary 1995-2001 Czech Republic 1995-2001 Bulgaria 1995-2001 Russia 1995-2001	0.55 out of 4.10 0.55 out of 4.81 0.54 out of 4.10 0.22 out of 0.79 0.71 out of 3.64 0.73 out of 2.27 0.45 out of 0.51 0.09 out of 1.12	0.13 out of 1.66	2.17 out of 1.66
Roeger (2001)	France, 1995-1999 Germany, 1995-1999 Italy, 1995-1999 UK, 1995-1999 US, 1995-1999	0.3 0.3 0.3 0.4 0.7		
RWI & Gordon (2002)	Germany 1990-95 1995-00	0.44 0.45		
Schreyer (2000)	Canada 1990-96 France 1990-96 Germany 1990-96 Italy 1990-96 Japan 1990-96 UK 1990-96 US 1990-96	0.28 out of 1.7[35] 0.17 out of 0.9 0.19 out of 1.8 0.12 out of 1.2 0.19 out of 1.8 0.28 out of 2.1 0.42 out of 3.0		
Sichel (1997) & (1999)	US 1980-92 US 1987-93 US 1996-98	0.2 out of 2.3 0.15 out of 2.0 0.35 out 4.2		
Niininen (2001)	Finland 1983-96 Finland 1991-96	0.38 out of 2.4 0.33 out of 0.5		
Jeong et al. (2001)	S. Korea 1980-95 S. Korea 1990-95	2.54 out of 7.9 2.71 out of 7.5		
Wong (2001)	Singapore 1977-97	1.46 out of 7.8		

Colecchia & Schreyer (2001)	Austria 1990-95 1995-00 Canada 1990-95 1995-00 Finland 1990-95 1995-00 France 1990-95 1995-00 Germany 1990-95 1995-00 Italy 1990-95 1995-00 Japan 1990-95 1995-00 UK 1990-95 1995-00 US 1990-95 1995-00	0.48 out of 3.4 0.68 out of 4.6 0.30 out of 1.8 0.57 out of 4.2 0.24 out of 0.7 0.62 out of 5.6 0.18 out of 1.0 0.35 out of 2.8 0.30 out of 2.2 0.38 out of 2.1 0.21 out of 1.4 0.36 out of 1.9 0.31 out of 1.3 0.38 out of 1.1 0.21 out of 2.1 0.48 out of 3.6 0.97 out of 2.6 1.71 out of 4.4		
Timmer, et al. (2003)	US 1995-2001 EU 1995-2001 Ireland 1995-2001 Finland 1995-2001 Greece 1995-2001 Spain 1995-2001 Portugal 1995-2001 Netherlad 1995-2001 Sweden 1995-2001 UK 1995-2001 France 1995-2001 Belgium 1995-2001 Denmark 1995-2001 Austria 1995-2001 Italy 1995-2001 Germany 1995-2001	0.8 out of 3.5 0.5 out of 2.4 0.8 out of 8.9 0.7 out of 4.5 0.5 out of 3.6 0.3 out of 3.7 0.4 out of 3.4 0.6 out of 3.3 0.8 out of 2.8 0.7 out of 2.8 0.3 out of 2.6 0.7 out of 2.5 0.7 out of 2.5 0.4 out of 2.4 0.4 out of 1.9 0.4 out of 1.5	0.7 out of 1.8 0.4 out of 1.4 0.7 out of 5.5 0.5 out of 3.2 0.7 out of 3.0 0.4 out of 2.7 0.7 out of 2.3 0.3 out of 2.1 0.8 out of 1.9 0.6 out of 1.8 0.4 out of 1.7 0.3 out of 1.7 0.6 out of 1.7 0.4 out of 1.1 0.4 out of 0.1 0.2 out of -0.4	0.8 out of 1.8 0.5 out of 1.4 3.6 out of 5.5 1.7 out of 3.2 2.7 out of 3.0 1.3 out of 2.7 1.1out of 2.3 0.5 out of 2.1 0.7 out of 1.9 0.3 out of 1.8 0.9 out of 1.7 0.9 out of 1.7 0.5 out of 1.7 0.1 out of 1.1 -0.1 out of 0.1 -0.6 out of -0.4
US Council of Economic Advisors (2001)	US, 1995-2000		0.62 out of 1.63	0.18 out of 1.63
van der Wiel (2000)	Netherlands 1991-95 1996-99	0.20 0.23		

Table 4.2. Summary results of some other types of empirical studies

Author	Method	Country/Time Coverage	Findings
Bruinshoodf & Ter Weel (1998)	OLS	Netherlands, 1992 &1996	Higher technology/R&D intensity industry has higher wage premium.
Dewan & Kraemer (2000)	OLS on Cobb-Douglas	36 Countries 1985-93	IT Capital Investment has a positive impact on output in developed countries but *not* in developing countries
Gurbaxani & Melville, Kraemer (2001)	OLS on Cobb-Douglas	US, firm level data 1987-94	Investment in mainframe computers and PCs has positive return to production.
Gurbaxani &Town (2001)	GMM on Cobb-Douglas	US, firm level data 1986-93	IT investment affects productivity in durable goods sectors, not in non-durable sectors.
Kiiski & Pohjola (2001)	OLS	OECD Countries and countries with more than 50 Internet hosts 1995-2000	GDP per capita and Internet access costs determine the growth in computer hosts per capita. Investment in education determines Internet penetration in a larger sample of countries, but not in OECD countries
Kraemer & Dedrick (2001)	Pearson Correlation	12 Asia Pacific Countries 1984-1990	Higher IT investment growth correlates with higher GDP growth and productivity growth.
Lee and Gholami (2002)	Granger Causality	16 countries, 1970-99	Little evidence of causal relationship between IT and economic growth
Lee, Oh, & Seo (2002)	OLS on Catch-up Models	Seventeen OECD countries, 1991-7	IT investment leads to higher productivity. Disparity in IT investment enlarges the gap in economic growth among OECD countries
Morissette & Drolet (1998)	OLS	Canada, 1994	The ability to use PC and fax increases wage rate.
Lee & Alba (2001)	Geweke-type Causality	14 countries, 1967-93	Little evidence of causal relationship between R&D expenditure and economic growth
Pohjola (2001a)	OLS on Cobb-Douglas	39 countries 1980-95	IT investment has a strong impact on growth
Pohjola (2002)	OLS on Cobb-Douglas	42 countries 1985-99	No significant relationship between ICT investment and economic growth
Quibria et al (2003)	OLS	100 Countries 1992-2002	Income, education and ICT infrastructure are three important determinants of ICT diffusion.

Endnotes

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[1] Critics remain, however, including Gordon (2000) who believes that ICT does not have the potential to raise growth as much as the great innovations of electricity, the dynamo and the internal combustion engine.
[2] See Appendix for a full list of the 55 countries
[3] The *Review of Income and Wealth* dedicated a special issue to the *New Economy* in March 2002 as did the *Journal of Policy Modelling* with its Special Silver Anniversary Issue; *The New Economy and Growth* issue 5, 2003, and the *Oxford Review of Economic Policy, volume 18, no. 3, 2002.*
[4] A partial survey can be found in Qiangi et al., (2003).
[5]Qiang et al. (2003) consider that there are three channels through which ICT can influence economic growth: 1. TFP growth in sectors producing ICT; 2. Capital deepening; 3. TFP growth through reorganization and ICT usage. Because of argument presented in Carlaw and Lipsey (2003) and Lipsey and Carlaw (2004) on the interpretation of TFP we choose not to follow this approach.
[6] ICT spending comprises spending on IT hardware, software, IT services, internal, and other office equipment plus telecommunications.
[7] Even the notion of existence of a steady-state.
[8] See Barro (1999) for details.
[9] In Solow (1957), the estimated value of α is around 0.35 and β is 0.65.
[10] This is an interpretation that is widely disputed in the literature (see for examples, Hulton (2000) and Jorgensons (1995)) In particular Carlaw and Lipsey (2003) and Lipsey and Carlaw (2004) show that TFP at best interpreted as a measure of unpaid for spillovers, but is certainly not a measure of technological change. Carlaw (2004) shows that under certain modelling specifications TFP is actually negatively correlated with diffusions of GPTs and supports this theoretical prediction with evidence from the Australian national accounts.
[11] Each data source typically has its own data collection approach and corresponding deflators, such that it is necessary for researchers to understand these characteristics before using the data.
[12] http://www.idc-cema.com
[13] http://www.eito.com/index-eito.html
[14] http://www.oecd.org/sti/stan
[15] http://www.ggdc.net
[16] http://www.nua.ie/surveys/
[17] http://www.itu.int/ITU-D/ict/
[18] Although an extensive review of the literature, this section does not claim to be an exhaustive. Several empirical studies encompass results from more recent work. This is the case for example, in several papers by van Ark, Piatkowski and Daveri where not all their individual papers will be reviewed and reported. Interested readers are encouraged to consult the following WWW sites on a regular basis: www.tiger.edu.pl (the WWW site for (Transformation, Integration and Globalization Economic Research Centrum), TIGER Working papers; http://www.ggdc.net/ (the WWW site for the Groningen Growth and Development Centre); and www.oecd.org (the OECD, see ICT portal).
[19] van Ark (2002) and van Ark et al. (2002) provide excellent reviews of the issues and results for the European Union countries with some comparsions to particularly the US.
[20] In Solow (1956)'s estimation, α=0.35, β=0.65, and α+ β=1.
[21] Generalised Method of Moments
[22] Marginal rate of Technical Substitution
[23] Which many regard as total factor productivity (TFP).
[24] OECD STAN Industry Structural Analysis Database
[25] The World Information Technology and Services Alliance , (WITSA)
[26] International Data Corporation (IDC),
[27] United States Bureau of Economic Analysis (BEA)
[28] Compustat and Computer Intelligence InfoCorp (CII)
[29] United Nation Industrial Development Organisation (UNIDO)
[30] General Social Survey (GSS)
[31] UK's Office for National Statistics (ONS)
[32] International Telecommunications Union, (ITU)
[33] Groningen Growth and Development Centre (GGDC)
[34] Annual Labour Productivity (ALP)
[35] Canada's ICT capital accounts for 0.28 percent out of 1.7 percent annual GDP growth in 1990-96.