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Long Term Implications of the ICT Revolution: Applying the Lessons of Growth Theory and Growth Accounting

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Abstract
How big a boost to long run growth can countries expect from the ICT revolution? I use the results of growth accounting and the insights from a two-sector growth model to answer this question. The use of a two-sector rather than a one-sector model is required because of the very rapid rate at which the prices of ICT products have fallen in the past and are expected to fall in the future. According to the two-sector model, the main boost to growth comes from ICT use, not ICT production. Even a country which has zero ICT production can benefit via improving terms of trade. In the long run, the falling relative price of ICT products boosts the growth of GDP and consumption by inducing faster accumulation of ICT capital. I quantify this effect on the long run growth rate of 15 European and 4 non-European countries, using data from the EU KLEMS database. The ICT intensity of production (the ICT income share) is much lower in many European countries than it is in the United States or Sweden. Nevertheless the contribution to the long run growth of labour productivity stemming from even the current levels of ICT intensity is substantial: about half a percent per annum on average in the countries studied here. Eventually, the ICT revolution may diffuse more widely so ICT intensity may reach at least the same level as currently in the U.S. or Sweden, which would add a further 0.2 percentage points per annum to long run growth.

Keywords: Potential output, productivity, ICT, two-sector model, growth accounting, terms of trade
JEL Classifications: E23, F43, O41, 047

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1. Introduction[1]

1.1 The approach

This paper introduces a method for projecting the growth of potential output and labour productivity, based on a two-sector model of economic growth. I use this model to make projections of the impact of information and communication technologies (ICT) on the long run growth rate of 19 countries, 15 inside and four outside the European Union. The distinctive feature of my approach is the use of a two-sector model, in which the first sector produces consumer goods and non-ICT capital goods while the second sector produces ICT products; ICT products can also be imported. ICT products comprise here computers (and related equipment), software, and communications equipment. The approach is also distinctive in employing an open economy framework.

There is considerable interest in policy circles in making long run projections. A number of workers in central banks, such as the Federal Reserve, the Bank of Canada and the Banque de France, have been interested in projecting long run (potential) output (see e.g. Cahn and Saint-Guilhem (2006)). The method I propose here is closest to that of Jorgenson, Ho and Stiroh (2004) and (2007), who make projections for the U.S., though mine is more explicitly based on a growth model.

Why should a central bank (or anyone else) be interested in potential output? The most obvious reason is that a central bank needs to take a view as to where the economy currently is in relation to its long run growth path. Growth theory tells us that in the absence of shocks there is a tendency for the economy to approach ever closer to its long run growth path. So measuring the gap between actual and long run output will assist a central bank in judging whether an observed increase in output is due to a shift in aggregate demand or to a shift in aggregate supply. A related reason for interest in long run projections is that central banks base their forecasts on models which include a production function. The production function contains a parameter which represents the growth rate of total factor productivity (TFP) or the growth rate of labour-augmenting technical progress. The work reported here can help inform a choice for the value of this parameter.

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1 This paper draws on earlier, unpublished work done at the Bank of England, in collaboration with James Smith. Neither the Bank nor James Smith has any responsibility for the present paper.

A projection of long run output could employ a purely statistical approach. For example one could fit a time series model to GDP or GDP per hour to obtain projections. I have chosen to adopt a more structural approach, in which I attempt to explain and quantify some of the factors behind long run growth. I believe this approach is more helpful for policy makers than a black box one.

The projections presented here are long run. They take no account of the effects of the current financial crisis and the recession. To do so would go well beyond the scope of the paper and at the moment would be excessively speculative. But arguably, the main effect of the recession will be on the long run *level* of output, rather than on its growth rate. So these long run projections still retain their interest, I hope.[2]

The empirical basis of the present approach is the EU KLEMS database (O'Mahony and Timmer, 2009). I use this because I am interested in developing projections for the market sector, i.e. excluding the activities of government where output is difficult to measure. In practice, this means excluding the three industries labelled Public administration and defence, Education, and Health and Social Work. This database is also appropriate because it uses a common-across-countries methodology for measuring capital, including in particular ICT capital.

1.2 The importance of ICT

The approach adopted here recognises the central importance of ICT in the modern world. After the growth rate of U.S. labour productivity started to rise in the latter half of the 1990s, a number of highly influential growth accounting studies were published. These included Oliner and Sichel (2000) and (2002), Jorgenson and Stiroh (2000a) and (2000b), Stiroh (2002), and Jorgenson, Ho and Stiroh (2004a, 2004b and 2007). These studies all attributed a high proportion of the productivity resurgence to ICT, and found that most of the improvement was due to the *use* of ICT equipment by other industries (capital deepening) rather than to the *production* of ICT equipment by the ICT industries themselves. Similar studies have been published for the U.K. (Oulton (2002); Oulton and Srinivasan (2005); Marrano *et al*. (2009)), and for the G7 (Schreyer (2000)); a U.S.-U.K. comparison is Basu *et al.* (2004) and an EU-U.S. comparison is van Ark, O'Mahony and Timmer (2008). These all

[2] Perron (1989) found that the Great Depression had a permanent effect on the level of U.S. GDP but no effect on its long run growth rate.

find a very important role for ICT capital deepening in accounting for the growth of productivity in the different countries. It is true that some observers questioned the growth accounting methodology and remained sceptical of the true importance of ICT, especially in the light of the dotcom bust of 2000 and the subsequent U.S. recession. But the fact that U.S. productivity growth has continued to be rapid in the first decade of the present century and that ICT investment has recovered to reach levels substantially higher than at the height of the dotcom boom has convinced most observers, including even initial sceptics (see e.g. Gordon (2003)) that investment in ICT is a very important part of the story, at least as a proximate cause (Oliner *et al*. (2007)). The conclusions from growth accounting now receive confirmation from micro studies: see e.g. Brynjolfsson *et al.* (2002), Brynjolfsson and Hitt (2003), Bloom *et al*. (2007), and Draca *et al.* (2006).

By their nature academic studies are always somewhat out of date, at least when they come to be published. So some more recent data is worth noting. Those who think that the ICT boom of the late 1990s was all irrational exuberance, associated with dotcom fever and Y2K hysteria, might like to note that in the U.S. the net stock of computers was 109% higher in 2007 than it had been in 2000, while the net stocks of software and communications equipment were 53% and 45% higher respectively (source: Bureau of Economic Analysis, Fixed Asset Tables, Table 2.2, available at www.bea.gov). The increase in the stock of communications equipment is particularly noteworthy given that many observers thought that the end of the ICT boom left the U.S. with considerable surplus capacity in fibre optic cables. So growth has been substantial even if at a slower rate than in the 1990s.

It is also useful to consider ICT in historical context: how does it compare with the great inventions of the past (Gordon, 2000)? ICT is now frequently regarded as a general purpose technology or GPT, defined by Lipsey *et al*. (2005, page 98) as follows: 'A GPT is a single generic technology, recognisable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects'. Earlier examples of GPTs are steam technology and electricity. Steam technology is usually considered central to the Industrial Revolution. But Crafts (2004) argues that the impact of ICT on labour productivity in the modern era has been greater than that of steam in the 19th century. Using the same standard growth accounting methodology employed in the studies already cited, he finds that the maximal impact of steam technology on labour productivity growth was 0.41% per year, which occurred in the period 1850-1870 (his Table 8); here the "impact of steam technology" means the contributions of stationary steam engines, railways, and steamships via both TFP and capital deepening. He points out that, at an annual rate, this is less than the estimated effect of ICT on U.S. labour productivity growth over 1974-90, which was 0.68% per year; the latter figure comes from Oliner and Sichel (2002, Table 1). Steam would look still less impressive if the comparison with ICT was extended to include the period since 1990. The main reason why steam's impact was lower than that of ICT, at least for the periods for which comparison is possible, is that the rate of decline of steam's relative price, due to faster technical progress in steam engines than in the rest of the economy, was quite modest for much of the nineteenth century.

1.3 Plan of the paper

Section 2 sets out the familiar one-sector (Solow) growth model and explains how it can be used to make projections. I then argue that this model is inappropriate for dealing with the effects of the ICT revolution and some of its predictions are implausible: for example the model predicts that a small open economy without an ICT-producing sector gets no benefit whatsoever from the ICT revolution despite enjoying continuously improving terms of trade. Moreover when calibrated using parameter values derived from a growth accounting study the model does not explain recent U.K. growth very well. This failure helps to motivate the two-sector model, introduced in section 3. The latter explains how even a small country which imports all of its ICT capital can still benefit from the ICT revolution. The two-sector model requires only a small number of parameters, most of which can be estimated from the EU KLEMS database, as explained in Section 4. Section 5 presents projections based on the two-sector model and Section 6 concludes.

2. Making projections with the one-sector growth model

I start with the textbook, one-sector (Solow) model, augmented to include human capital. Consideration of this model will motivate the move to a two-sector model. Here we assume just one sector whose output can be used for either consumption or investment. For simplicity and for consistency with the two-sector model below, I assume that the production function is Cobb-Douglas with constant returns. In familiar notation, the equations of the model are:

$$Y = C + I = BK^{\gamma}[hH]^{1-\gamma}, \quad 0 < \gamma < 1 \tag{1}$$

and

$$\dot{K} = I - \delta K \tag{2}$$

where B is the level of total factor productivity (TFP), H is hours worked, h is the average level of skill (human capital) per worker, and δ is the geometric rate of decay (depreciation). In per hour terms,

$$y = \frac{Y}{H} = Bh^{1-\gamma}k^{\gamma} \tag{3}$$

putting $k = K/H$. Hours worked (H) are assumed to grow exogenously at rate n and human capital at the exogenous rate g_h. Treating g_h as exogenous may be justified since education does not form part of our definition of the market sector. Given that constant returns are being assumed, we also assume perfect competition in goods and input markets. Profit-maximisation then requires that the real user cost of capital, here $r + \delta$, where r is the real rate of interest, should equal the marginal product of capital:

$$r + \delta = \gamma \frac{Y}{K} = \gamma \frac{y}{k} \tag{4}$$

As is well-known, this model possesses a steady state in which the output-capital ratio (Y/K) is constant. Constancy of this ratio requires that the real interest rate should be constant too. Hence, differentiating the production function with respect to time, the steady state growth rate of output per hour is given by

$$\begin{aligned} \hat{y}^* &= \mu + (1-\gamma)g_h + \gamma\hat{k}^* \\ &= \frac{\mu}{1-\gamma} + g_h \end{aligned} \tag{5}$$

where a "hat" (^) denotes a growth rate, a star (*) denotes the steady state, and μ is the growth rate of TFP: $\mu = \hat{B}$. In the basic Solow model there is only one engine of growth, the exogenous growth of TFP. Here there is also a second engine, the growth of human capital. Physical capital plays an important role, but in the long run all capital deepening (growth of k) is induced by growth of TFP or growth of skill.[3]

In this model, forecasting the long run growth rate of hourly labour productivity (y) is

[3] The derivation assumes a Cobb-Douglas production function but this is only for comparability with what follows. Essentially the same results could be derived from any neo-classical production function with purely labour-augmenting technical progress.

fairly straightforward: it requires just a forecast of TFP growth (μ), an estimate of the labour share, and an estimate of the growth rate of skill. Assuming that inputs are paid their marginal products, TFP growth can be measured by

$$\mu = \hat{B} = \frac{\dot{Y}}{Y} - v_K\left(\frac{\dot{K}}{K}\right) - v_L\left(\frac{\dot{H}}{H}\right) - v_L\hat{h} \tag{6}$$

where $v_K\,(v_L)$ is the income share of capital (labour) and $v_K + v_L = 1$. (In terms of the model, $v_K = \gamma,\ v_L = 1-\gamma$). A forecast of TFP growth can be based on its own history, which empirically would be measured using discrete time:

$$\ln\left[\frac{B_t}{B_{t-1}}\right] = \ln\left[\frac{Y_t}{Y_{t-1}}\right] - \bar{v}_{K,t}\ln\left[\frac{K_t}{K_{t-1}}\right] - \bar{v}_{L,t}\ln\left[\frac{H_t}{H_{t-1}}\right] - \bar{v}_{L,t}\ln\left[\frac{h_t}{h_{t-1}}\right] \tag{7}$$

where $\bar{v}_{K,t} = \tfrac{1}{2}\left[v_{K,t} + v_{K,t-1}\right]$ and $\bar{v}_{L,t} = \tfrac{1}{2}\left[v_{L,t} + v_{L,t-1}\right]$ .Similarly, a forecast of the growth of skill could be based on its own past history. The latter could be measured by the difference between the growth of hours and a quality-adjusted index of the growth of hours. In the quality-adjusted index each type of labour is weighted by its wage. So quality is rising if the composition of the labour force is shifting towards more highly paid forms of work (for U.K. measures of skill growth, see Bell *et al*. (2005); similar measures appear in the EU KLEMS database).

I have calibrated the one-sector model on U.K. data over the period 1979-2003. I find that the model under-predicts the actual growth rate experienced over this period and that the discrepancy grows over time. This is the case whether or not we assume that the U.K. economy was in a steady state over this period. The details are in Annex B.

But there is a more fundamental reason why the one-sector model is inappropriate for studying the impact of the ICT revolution. Where does ICT appear in the solution for the equilibrium growth rate, equation (5)? If we applied the model to an economy with some ICT production, then the fact that TFP growth has been (and will probably continue to be) higher than in non-ICT industries will influence the past and projected future aggregate TFP growth rate. But suppose instead we are considering a small, open economy with no ICT production at all (not an unrealistic assumption). Then the one-sector model predicts zero impact from the ICT revolution. But surely the ability to import ICT capital at ever-declining prices must be beneficial to growth? As we are about to see, this is exactly what the two-sector model predicts.

3. A two–sector model[4]

3.1 The model for a closed economy

The one-sector model assumes in effect that there are no persistent changes in the relative prices of the myriad goods which make up a real economy. It thus fails to capture the most striking feature of recent economic history in the industrialised economies, namely the dramatic and persistent falls in the relative price of ICT investment goods. For example, in the United States between 1970 and 2007 the relative price of computers in terms of personal consumption was falling at an average rate of 20.32% per year; the relative price of the broader category of "information processing equipment and software" was falling at 6.44% per year (source: U.S. NIPAs: see Table 1). So I now consider a two-sector model in which the relative price of the good produced by the second sector is changing. Initially the economy is assumed to be closed.

I assume that the output of the first sector can be used either for consumption (C) or for investment (I_C); the output of the second sector, which we can think of as the sector producing ICT goods, can only be used for investment (I_{ICT}). For brevity, I refer to the sector producing consumption and non-ICT investment goods as just the consumption sector. The production function for this sector is given by

$$Y_C = B\left(K_C^C\right)^{\alpha}\left(K_{ICT}^C\right)^{\beta}\left(hH_C\right)^{1-\alpha-\beta}, \quad 0<\alpha,\beta<1,\ \alpha+\beta<1 \tag{8}$$

[4] The present model draws on Oulton (2007a); see also Greenwood and Krusell (2007). A model similar in structure to the present one but with a quite different interpretation is in Barro and Sala-i-Martin (1995), chapter 5. The two-sector model with faster technical progress in investment goods was revived by Whelan (2001) and applied by Martin (2001) to study the U.S. economy and by Cette *et al.* (2005) to compare France and the U.S. It was also employed by Bakhshi and Larsen (2005) to analyse the impact of macroeconomic shocks in the U.K. context. Oliner and Sichel (2002) employ the steady state of a five-sector model for some of their projections of the U.S. economy. For earlier work on two-sector models with discussion of stability issues (not treated here), see Burmeister and Dobell (1970). The main difference between the earlier work and the present paper is the extension of the two-sector model to an open economy.

where K_C^C, K_{ICT}^C are capital services of non-ICT and ICT capital respectively that are used by the consumption sector (here the superscript represents the industry), and H_C is hours worked in that sector. In per hour terms,

$$y_C = \frac{Y_C}{H_C} = B_C h^{1-\alpha-\beta} \left(k_C^C\right)^{\alpha} \left(k_{ICT}^C\right)^{\beta} \tag{9}$$

Here $k_C^C = \frac{K_C^C}{H_c}$ and $k_{ICT}^C = \frac{K_{ICT}^C}{H_c}$, the capital intensities in the consumption sector. I assume as before that skill is growing exogenously at rate g_h and that TFP in the consumption good sector (B_C) is growing at rate μ_C.

For the ICT-producing sector, I make a crucial, simplifying assumption: the production function is the same as in the consumption sector, except for TFP. As a result, in equilibrium the capital intensities will be the same in both sectors and equal to the whole-economy input endowments. The production function for the ICT sector is:

$$y_{ICT} = \frac{Y_{ICT}}{H_{ICT}} = B_{ICT} h^{1-\alpha-\beta} \left(k_C^{ICT}\right)^{\alpha} \left(k_{ICT}^{ICT}\right)^{\beta} \tag{10}$$

Here $k_C^{ICT} = \frac{K_C^{ICT}}{H_{ICT}}$ and $k_{ICT}^{ICT} = \frac{K_{ICT}^{ICT}}{H_{ICT}}$, the capital intensities. The growth rate of TFP in the ICT sector, $\mu_{ICT} = \hat{B}_{ICT}$, is assumed exogenous.

Next, input supplies must equal demands:

$$K_C = K_C^C + K_C^{ICT} \tag{11}$$

$$K_{ICT} = K_{ICT}^C + K_{ICT}^{ICT} \tag{12}$$

$$H = H_C + H_{ICT} \tag{13}$$

The accumulation equations, where I denotes investment and where δ_C, δ_{ICT} are the geometric rates of depreciation, are:

$$\dot{K}_C = I_C - \delta_C K_C \tag{14}$$

$$\dot{K}_{ICT} = I_{ICT} - \delta_{ICT} K_{ICT} \tag{15}$$

Since the economy is assumed to be closed, the supply-use balance equations are:

$$Y_C = C + I_C \tag{16}$$

$$Y_{ICT} = I_{ICT} \tag{17}$$

As before, hours worked (H) are assumed to grow exogenously at rate n ($\hat{H} = n$) and human capital at the exogenous rate g_h.

It is also useful to define the relative price of ICT goods relative to that of consumption goods, p: $p = P_{ICT} / P_C$ where P_{ICT}, P_C are the nominal prices of the ICT and consumer goods respectively.

3.2 The steady state

This completes the model. As shown in Annex A, the model possesses a steady state (defined as a state where the real interest rate and the proportion of aggregate hours allocated to each sector are constant) with the following properties. The growth rate of consumption per hour worked ($c = C / H$) is constant in the steady state:

$$\hat{c}^* = \frac{(1-\beta)\mu_C + \beta\mu_{ICT}}{(1-\alpha-\beta)} + g_h \qquad (18)$$

$$g = \frac{(1-\beta)\gamma_c + \beta\gamma_i}{1-\alpha-\beta} \quad \mathrm{I}$$

Annex A also shows that

$$\hat{p} = \mu_C - \mu_{ICT} < 0 \qquad (19)$$

$$g_p = \gamma_c - \gamma_i \quad \mathrm{II}$$

since by assumption $\mu_C < \mu_{ICT}$. So the steady state growth rate can also be written as:

$$\hat{c}^* = \frac{\mu_C - \beta\hat{p}}{(1-\alpha-\beta)} + g_h \qquad (20)$$

This second form of the solution is useful in the empirical work and also in the context of an open economy: see below.

To complete the solution of the model, the steady state growth rates of output per hour in the two sectors are:

$$\hat{y}_C^* = \hat{c}^*$$
$$(21)$$
$$y_{ICT}^* = \hat{c}^* - (\mu_C - \mu_{ICT}) = \hat{c}^* - \hat{p} > \hat{y}_C^*$$

The solutions for the growth rates of the other variables are

$$\hat{k}_C^* = \hat{i}_C^* = \hat{c}^*$$

y_c, k_c, c, i_c grow at g

$g_i = g - g_p$

$$\hat{k}_{ICT}^* = \hat{i}_{ICT}^* = \hat{c}^* - \hat{p} \qquad (22)$$

y_i, k_i, i_t grow at $g - g_p$ (faster)

Using I & II

$$g_i = \frac{(1-\beta)\gamma_c + \beta\gamma_i}{1-\alpha-\beta} - (\gamma_c - \gamma_i)$$
$$= \frac{(1-\beta)\gamma_c + \beta\gamma_i + (1-\alpha-\beta)(\gamma_i - \gamma_c)}{1-\alpha-\beta}$$
$$= \frac{(1-\beta)\gamma_c + \beta\gamma_i + (1-\alpha-\beta)\gamma_i - (1-\alpha-\beta)\gamma_c}{1-\alpha-\beta}$$
$$g_i = \frac{\alpha\gamma_c + (1-\alpha)\gamma_i}{1-\alpha-\beta} \quad \mathrm{III}$$

$$\hat{H}_C^* = \hat{H}_{ICT}^* = \hat{H} = n; \quad \hat{Y}_C^* = \hat{y}_C^* + n; \quad \hat{Y}_{ICT}^* = \hat{y}_{ICT}^* + n$$

These results are derived using the principle that the real marginal product of each type of capital must equal the real user cost plus the conditions required for a steady state.

Note that in steady state:

(1) Output and productivity of the consumption good grow less rapidly than does output and productivity of the ICT good.

(2) The stock of ICT capital grows faster than the stock of non-ICT capital.

(3) The growth of productivity in the consumption sector depends positively on the growth rates of TFP in the two sectors; the weight for TFP growth rate in the ICT sector is the income share of ICT, β, while that for non-ICT is the complement, $1-\beta$.

(4) These results enable us to show that the ratios of investment to GDP, the capital-output ratios and the savings ratio, all in value (current price) terms, are constant in the steady state.

Intuitively, where there were two engines of growth in the one-sector model, TFP and skills growth, there is now a third, TFP growth in the ICT sector which is faster than in the consumption sector. This third engine drives up the growth rate of consumption permanently.

A Divisia index of the steady state growth rate of real GDP (Y) can now be derived as:

$$\begin{aligned}\hat{Y}^* &= (1-w^*_{ICT})\hat{Y}^*_C + w^*_{ICT}\hat{Y}^*_{ICT} \\ &= (1-w^*_{ICT})\hat{y}^*_C + w^*_{ICT}\,\hat{y}^*_{ICT} + n \\ &= \hat{y}^*_C - w^*_{ICT}\,\hat{p} + \hat{H} \\ &= \frac{\mu_C - \left[\beta + (1-\alpha-\beta)\,w^*_{ICT}\right]\hat{p}}{(1-\alpha-\beta)} + g_h + n\end{aligned} \tag{23}$$

where $w^*_{ICT} = pY^*_{ICT}/(Y^*_C + pY^*_{ICT})$ is the steady state output share of the ICT sector and we have made use of equations (18)-(22). The growth rate of GDP per hour is obviously positively related to the two TFP growth rates. It is also positively related to (a) the income share of ICT capital (β) and (b) the share of ICT output in GDP (w^*_{ICT}). It is easy to see that real GDP grows more rapidly than real consumption in the steady state if the ICT output share is greater than zero (i.e. if $w^*_{ICT} > 0$). In fact, the steady state growth rate of consumption (given by equation (18)) is apparently independent of the ICT output share. But this is a bit misleading: the larger is the ICT income share (β), the larger must be the ICT output share (w^*_{ICT}), since all ICT products are by assumption produced at home. The relationship between the two shares is:[5]

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[5] The output share is: $w_{ICT} = pY_{ICT}/(Y_C + pY_{ICT})$ and from Annex A the income share is

$$w_{ICT} = \beta\left[\frac{\delta_{ICT} + \hat{K}_{ICT}}{r + \delta_{ICT} - \hat{p}}\right] \tag{24}$$

Equation (23) is the two-sector analogue of the one-sector solution of equation (5). In fact, if there is no difference between the TFP growth rates in the two sectors (i.e. $\hat{p} = 0$), then the two-sector model collapses back down to the one-sector one, and equation (23), and also equation (18), reduces to equation (5).[6]

3.3. The open economy

In many countries the ICT-producing sector is small or even zero. So does the model set out above have any relevance for them? The answer is yes, but to demonstrate this we have to extend the closed economy model of the preceding section to incorporate international trade. Consider a small, open economy whose comparative advantage is in the production of the consumption good; it may or may not produce any ICT goods. It exports part of its output of consumption goods in exchange for imports of the ICT good. The price of ICT goods in terms of consumption goods (p), the terms of trade, is exogenous for this economy; we assume that it is falling at a constant rate.

The supply-use balance equations must now be modified to include trade:

$$Y_C = C + I_C + X \tag{25}$$

$$Y_{ICT} = I_{ICT} - M \tag{26}$$

where X is the quantity of exports of non-ICT products and M is the quantity of imports of ICT capital goods.

The natural assumption for trade is that it must be balanced in the steady state:[7]

$\beta = [r + \delta_{ICT} - \hat{p}]pK_{ICT} / (Y_C + pY_{ICT})$. In the closed economy, $Y_{ICT} = I_{ICT}$ (see (15)). Equation (24) then follows from using (17). Hence the output share is positively related to the income share and this remains true in the steady state when it can be shown that the steady state growth rate of ICT capital is itself positively related to the parameter β (see equations (A22), (A29) and (A30) in Annex A).

[6] Interpreting $1 - \alpha - \beta$ in (23) as the share of labour and therefore equivalent to $1 - \gamma$ in equation (5).

[7] Alternatively we could assume that in steady state exports stand in a constant ratio to imports in current price terms; this would change very little.

$$X^{*} = pM^{*} \tag{27}$$

Consider a steady state in which the real interest rate and the proportions of aggregate hours allocated to the two sectors are constant. The “real rental price equals marginal product” rule implies, as shown in Annex A, exactly the same steady state growth rates as in the closed economy model, namely those of equations (18)-(23).

So the open-economy model turns out to be not very different from the closed-economy model. The steady state growth rate of consumption is the same in both models. And with international trade, countries can have different growth rates of GDP per hour even though they have the same growth rate of consumption per hour. These results may seem paradoxical but they really result from our assumption of competition. ICT producers earn only normal profit and all the benefits of innovation accrue to consumers, even when located abroad. Clearly this is a simplification since successful innovation surely generates monopoly profit, even if only temporarily. Nevertheless it may be a reasonable simplification; otherwise it would be hard to explain why ICT prices have fallen so rapidly.[8]

There is however one important difference between the closed and open economy models. As we have seen from equation (24), the ICT output share is positively related to the ICT income share in the closed economy but there need be no such relationship in the open economy: in effect international trade breaks the link between the two shares.

Consideration of the open economy shows how misleading the one-sector model can be. For that model predicts that the long run growth rate of a small economy which is completely specialised in the non-ICT good is determined entirely by TFP growth in that sector (and the labour share). So such an economy apparently derives no benefit at all from the ICT revolution. But we now see that this economy benefits in the form of improving terms of trade and the two-sector model allows us to quantify this effect.

[8] Nordhaus (2005) argues that the monopoly (Schumpeterian) profits of innovators are quite small in relation to GDP.

4. Implementing the two-sector model empirically

4.1 Measuring the ICT use and ICT output effects

The empirical counterpart of the theoretical equation (23), describing the steady state growth of GDP, can be written as follows:

$$\Delta \ln \overline{Y} = \frac{\Delta \ln \overline{B}_C - \left[\overline{v}_{K_{ICT}} + \overline{v}_L \overline{w}_{ICT}\right] \Delta \ln \overline{p}}{\overline{v}_L} + \overline{g}_h + \overline{g}_H \qquad (28)$$

where bars over variables indicate projected values; $\overline{v}_{K_{ICT}}$ is the projected income share of ICT capital, $\overline{v}_L$ is the projected income share of labour, and $\overline{g}_H$ is the projected growth rate of hours worked. Values for these parameters are required for medium/long run projections of GDP growth. The parameters and their relationship to model parameters are given in Table 2.

The scope of the present paper is a bit narrower since we are only trying to quantify the effect of ICT on productivity growth. We can therefore split equation (28) into an ICT and a non-ICT effect on aggregate productivity growth (real GDP per hour). The ICT effect can be further split between ICT use and ICT output, so we get:

Total ICT effect on productivity growth

$$= \text{ICT use effect} + \text{ICT output effect} \qquad (29)$$

$$= \left(\frac{\overline{v}_{K_{ICT}}}{\overline{v}_L}\right)\left(-\Delta \ln \overline{p}\right) + \overline{w}_{ICT}\left(-\Delta \ln \overline{p}\right)$$

So to compute the ICT effect on productivity growth we need to measure just four parameters: the income shares of ICT capital and of labour, $\overline{v}_{K_{ICT}}$ and $\overline{v}_L$, the ICT output share, $\overline{w}_{ICT}$, and the (negative) growth rate of the relative price of ICT goods, $\Delta \ln \overline{p}$.

The income and output shares can be estimated from the EU KLEMS database, which is an internationally comparable set of national accounts: see O'Mahony and Timmer for a full discussion.[9] In EU KLEMS, the ICT income share is measured as profits attributable to ICT capital divided by current price value added in the market sector. ICT capital comprises

9 The database is freely available at www.euklems.net. I used the November 2009 release which covers the period 1970-2007 though not all years are available for all countries.

computers, software and communications equipment. Profits attributable to a particular type of ICT capital equal the rental price of that type times the real stock of that type. In turn the rental price equals the rate of return plus the depreciation rate minus the rate of capital gain, all multiplied by the asset price of that type of ICT capital (the Hall-Jorgenson formula).[10] Profits attributable to ICT capital are then the sum of profits attributable to each type. The market sector is defined as GDP excluding those sectors which are predominantly governmental or non-profit: health, education, and public administration and defence (NACE sectors L-N plus real estate, industry 70).[11]

The ICT output share can also be derived from EU KLEMS as value added in "Electrical and optical equipment" (NACE industries 30-33) divided by value added in the market sector. Unfortunately, the definition of ICT industries does not quite correspond to that of ICT capital. The main difference is that software is excluded from the output definition (software is counted as part of "Finance and business, except real estate"). On the other hand on the goods side the definition of ICT output is wider than just computers and communications equipment. The ICT income and output shares are available for 19 countries, 15 in the EU and four non-EU (Australia, Canada, Japan and the United States).

4.2 The growth rate of the relative price of ICT ($\Delta \ln \bar{p}$)

Most researchers who study the impact of ICT consider the U.S. price indices to be more reliable than their counterparts in other countries (Schreyer (2002), Oulton (2001); O'Mahony and van Ark (2003); Oulton and Srinivasan (2005)).[12] I follow suit here and measure the relative price of ICT as the U.S. price of ICT equipment (computers, software

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[10] In EU KLEMS the rate of return in the cost of capital formula is estimated by the ex post method. For a discussion of whether ex post or ex ante measures are more appropriate, see Oulton (2007b) and Oulton and Aznar-Rincon (2010).

[11] The ICT income share is measured as (*CAPIT* x *CAP*)/*VA* where *CAPIT* is capital compensation attributable to ICT capital as a share of total capital compensation, *CAP* is total capital compensation and *VA* is value added, both in current prices; *CAPIT*, *CAP* and *VA* are all EU KLEMS variables.

[12] In the U.K. the Office for National Statistics now employs a similar methodology to that of the U.S. Bureau of Economic Analysis to measure the price of computers, but this new methodology has only been applied to recent years of the computer price series.

and communications equipment) relative to the price of gross value added in the non-farm business sector (the latter being close to the EU KLEMS market sector). As Table 1 shows, the price of ICT equipment has fallen at a remarkably constant rate since 1970. The average growth rate was *minus* 8.28 percent per year over 1970-89 and *minus* 7.96 percent per year over 1989-2007. Within the ICT aggregate, computer prices were declining much more rapidly. It is possible that if the same effort were devoted to allowing for quality change in software and communications equipment as has been applied to computers, the rate of decline of software and communications equipment prices would be found to have been understated in Table 1. However that may be, it is also the case that over the latest period, 2000-2007, the rate of decline of ICT prices has slowed somewhat, to *minus* 6.44 percent per year, mainly because the rate of decline of computer prices has slowed a bit. To err on the conservative side in the projections, I assume that ICT relative prices will fall at 7% per annum.[13]

5. Projections of the long run impact of ICT on growth

5.1 The importance of ICT

The importance of ICT output, measured by value added in the ICT industries as a percentage of value added in the market sector, varies widely across the 19 countries studied here. The lowest proportion is in Australia, 0.79% and the highest is in Finland, 8.21%; the U.S. lies in the middle of this range of countries at 3.10% (Table 3, column 1, and Chart 2).[14] In many countries the share has been stagnant or falling since 1970 (Chart 2). This is quite consistent

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[13] Jorgenson *et al.* (2007) present estimates of TFP growth rates in the U.S. ICT-producing sector. Their low estimate is 8.05 per cent per year (based on the average growth rate for 1973-95) and their high one is 10.77 per cent per year (based on the average growth rate for 1995-2005). This suggests that the relative price of ICT equipment will be falling at between 7.75 and 10.15 per cent per year. The International Technology Roadmap for Semiconductors suggests that technical progress in semiconductors, the foundation for the rapidly declining relative price of ICT equipment, will continue at a rapid rate over their forecast horizon which runs to 2024 (ITRS, 2009).

[14] These shares are averages over the years from 2000 till the latest year available for each country, usually 2007 except for Canada (2004) and Japan and Slovenia (2006).

with the idea that the location of ICT production is determined by comparative advantage and may lie outside both Europe and North America.

ICT income shares present quite a different picture: see Table 3, column 2 and Chart 1. In fact, the rank correlation coefficient between the ICT output and income shares is minus 0.16 and not significant. The country with the lowest ICT income share is Ireland at 2.88%, despite having the second highest output share (7.21%). The leading country here is Sweden at 6.93% with the U.S. very close behind at 6.83% and the U.K third at 6.34%. Italy is also low (3.52%) as are France (4.91%) and Germany (4.45%). It is interesting that some of the new EU countries such as Hungary (5.08%) and the Czech Republic (4.54%) do about as well on this measure as France and Germany.

Chart 1 shows the time path of the ICT income shares for individual countries, 1970-2007. Where data are available for a sufficient number of years we see an upward trend though with some levelling off in most countries since 2000.

These ICT income shares can be thought of as measures of the extent of the diffusion of these technologies, or more romantically, of the extent to which the ICT revolution has been exported around the world. Two interesting research questions are: (1) Will the ICT income share go on rising in the most advanced countries? And (2) will the ICT income share in the relatively backward countries eventually catch up with the share in the advanced ones? The evidence of Chart 1 suggests that the answer to the first question is a tentative no. As for the second question, Cette and Lopez (2008) find that the strongest factor explaining differences in the extent of ICT intensity across countries is the proportion of the working age population with some higher education. Next in importance come labour and product market rigidities. Differences in educational attainment may erode naturally over time. But in any case these factors are all amenable to policy. So catch-up would seem to depend on the success or otherwise of policies to raise educational attainment and reduce rigidities.

5.2 ICT growth effects

I now ask: what is the contribution of ICT to long run growth, assuming that each country's income and output shares remain at their average levels over 2000-2007? This means assuming that the steady state solution of the two-sector growth model applies, after a period of adjustment during which the income share of ICT has risen to its long run value. The answer, derived by applying equation (29), is in columns 3 and 4 of Table 3, and in Charts 5, 6 and 7. Recall that I am assuming here that the relative prices of ICT products will continue to fall at 7 per cent per annum. Recall too that the ICT output effect (column 3 of Table 3 and Chart 6) affects long run GDP (and productivity) growth but not consumption growth. The main findings are:

1. The ICT use effect ranges from 0.28 p.p.p.a. (percentage points per annum) in Slovenia to 0.70 p.p.p.a. in Sweden (Chart 5).
2. The simple cross-country average of the output effect is 0.24 p.p.p.a. and of the use effect is 0.54 p.p.p.a. (Chart 6). The ICT use effect is larger, often much larger, than the output effect for all countries except Ireland (Chart 7).
3. The largest output effect is in Finland (0.57 p.p.p.a.) but even here the use effect is larger (0.67 p.p.p.a.).

This means that for the average country (amongst these 19), ICT will contribute 0.54 p.p.p.a. to the future growth rates of consumption per hour and GDP per hour, assuming that the current level of ICT intensity is maintained (but not increased). This is a substantial effect given that from 1990 to 2007 output per hour in these countries' market sectors has been growing on average at 2.55% p.a.[15]

We could also ask, what will be the effect on growth if ICT intensity (the ICT income share) rises to equal the level found in the most ICT-intensive country, Sweden? The answer, in the form of the difference between growth at each country's own ICT income share and growth if the share were at the Swedish level, is in column 6 of Table 3 and Chart 8. If all countries enjoyed the Swedish level of ICT use, ICT would contribute 0.74 p.p.p.a. to growth, compared to an average of 0.54 p.p.p.a. with current ICT use levels. In other words, if all the other 18 countries raised their ICT use to Swedish levels they would enjoy on average a boost to growth of 0.20 p.p.p.a. The largest beneficiary would be Ireland with an extra 0.55 p.p.p.a.

6. Conclusions

Growth accounting studies have shown that the ICT revolution has been hugely important for productivity growth in the last twenty years or so. But without a model it is difficult to get a

[15] The range is from 1.14 % p.a. in Spain to 5.05% p.a. in Slovenia. Source: EU KLEMS.

handle on likely future growth stemming from ICT. I have argued that the workhorse, one-sector model is inappropriate for this task and moreover does not fit the facts of the past, at least in the U.K. But a two-sector model, in which the first sector produces consumer goods and non-ICT capital goods while the second sector produces ICT capital goods, does provide the necessary framework. Moreover it is justified theoretically by the central fact of the ICT revolution, the dramatic and continuing fall in the prices of ICT products.

According to the two-sector model, the long run effects of ICT on the growth of consumption and GDP per hour are captured by the *ICT use effect*, which depends on just three parameters: the income share of labour, the income share of ICT capital (profit attributable to ICT capital as a share of GDP), and the rate at which the relative price of ICT capital is declining. In addition, the growth of GDP per hour, but not of consumption per hour, is also affected by the *ICT output effect*, which depends on the share of ICT *output* in GDP and the same relative price parameter. The reason why the ICT output effect does not influence the long run growth of consumption is that ICT products are assumed (realistically) to be available through international trade even if they are not produced at home.

I find that the ICT use effect dominates the output effect for 18 of the 19 countries studied here. Assuming an ongoing 7% rate of decline in the relative price of ICT products, and that ICT intensity remains at current levels, then ICT use will add on average 0.54 percentage points per annum to the growth of consumption in future. If ICT intensity were to rise to the level currently found in Sweden, then ICT use would contribute 0.74 percentage points per annum to growth. This suggests that there is a continuing payoff to policies aimed at removing obstacles to the wider adoption of ICT.

Table 1
Average growth rate of relative prices of ICT equipment in the United States, per cent per year

	1970-1989	*1989-2007*	*2000-2007*	*1970-2007*
Computers	-22.22	-18.30	-14.80	-20.32
Software	-5.24	-3.49	-2.86	-4.39
Communications equipment	-1.79	-5.16	-6.60	-3.43
ICT (average of above)	-8.28	-7.96	-6.44	-8.12

Note ICT prices are relative to the price index of the non-farm business sector.
Source U.S. Bureau of Economic Analysis, National Income and Product Accounts, Tables 5.5.4 and 1.3.4 (www.bea.gov, accessed 9 November 2010).

Table 2
Parameters required for the two-sector model

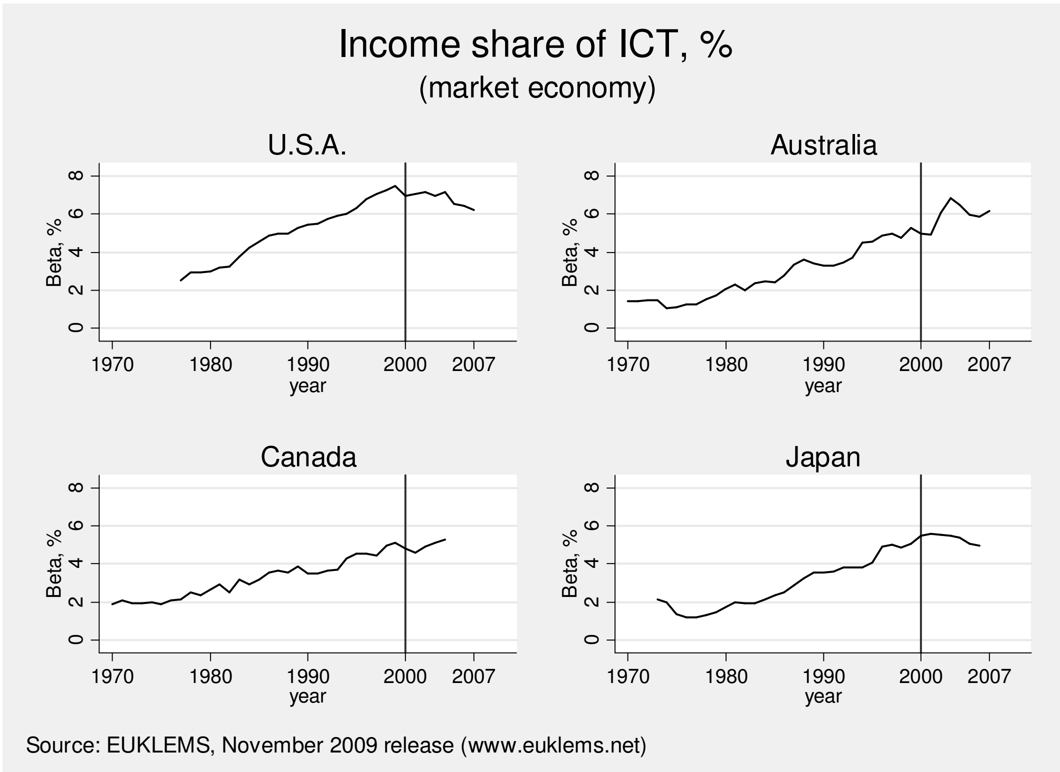
Empirical parameter	*Meaning*	*Model parameter(s)*
$\overline{v}_L$	income share of labour in GDP	$1-\alpha-\beta$
$\overline{v}_{K_{ICT}}$	income share of ICT capital in GDP	β
$\overline{w}_{ICT}$	share of output of ICT sector in GDP	w^*_{ICT}
$\Delta \ln \overline{B}_C$	TFP growth rate in non – ICT sector	μ_C
$\Delta \ln \overline{p}$	Growth rate of relative price of ICT goods	$\mu_C - \mu_{ICT} = \hat{p}$
$\overline{g}_H$	growth rate of total hours worked	n
$\overline{g}_h$	growth rate of average level of skill (human capital) per worker	g_h

Table 3
The effects of ICT on long run growth

Country	*ICT output share per cent*	*ICT income share per cent*	*ICT output effect p.p.p.a.*	*ICT use effect (a) own β p.p.p.a.*	*ICT use effect (b) Swedish β p.p.p.a.*	*Difference p.p.p.a.*
	(1)	(2)	(3)	(4)	(5)	(6)
Australia	0.79	5.91	0.06	0.66	0.77	0.11
Austria	3.15	4.25	0.22	0.46	0.76	0.29
Belgium	1.90	6.03	0.13	0.64	0.73	0.09
Canada	1.34	4.95	0.09	0.58	0.81	0.23
Czech Rep.	3.81	4.54	0.27	0.53	0.81	0.28
Denmark	2.88	6.13	0.20	0.62	0.70	0.08
Spain	1.39	4.83	0.10	0.53	0.76	0.23
Finland	8.21	6.14	0.57	0.67	0.76	0.09
France	2.46	4.91	0.17	0.48	0.68	0.20
Germany	4.75	4.45	0.33	0.44	0.68	0.24
Hungary	6.27	5.08	0.44	0.58	0.79	0.21
Ireland	7.24	2.88	0.51	0.39	0.94	0.55
Italy	2.67	3.52	0.19	0.36	0.70	0.35
Japan	5.14	5.36	0.36	0.61	0.79	0.18
Netherlands	1.36	4.97	0.10	0.51	0.71	0.20
Slovenia	3.97	3.09	0.28	0.28	0.62	0.35
Sweden	3.39	6.93	0.24	0.70	0.70	0.00
U.K.	2.26	6.34	0.16	0.60	0.66	0.06
U.S.A.	3.10	6.83	0.22	0.70	0.71	0.01

Source Own calculations and EU KLEMS database, November 2009 release.
Notes ICT use and output effects calculated in accordance with equation (29). The relative price of ICT products is assumed to fall at 7% p.a. in future. Shares are averages over 2000 till the latest year available which is 2007 except for Canada (2004), and Japan and Slovenia (2006). p.p.p.a: percentage points per annum.

Chart 1
ICT income shares in the market economy (β), 19 countries, per cent



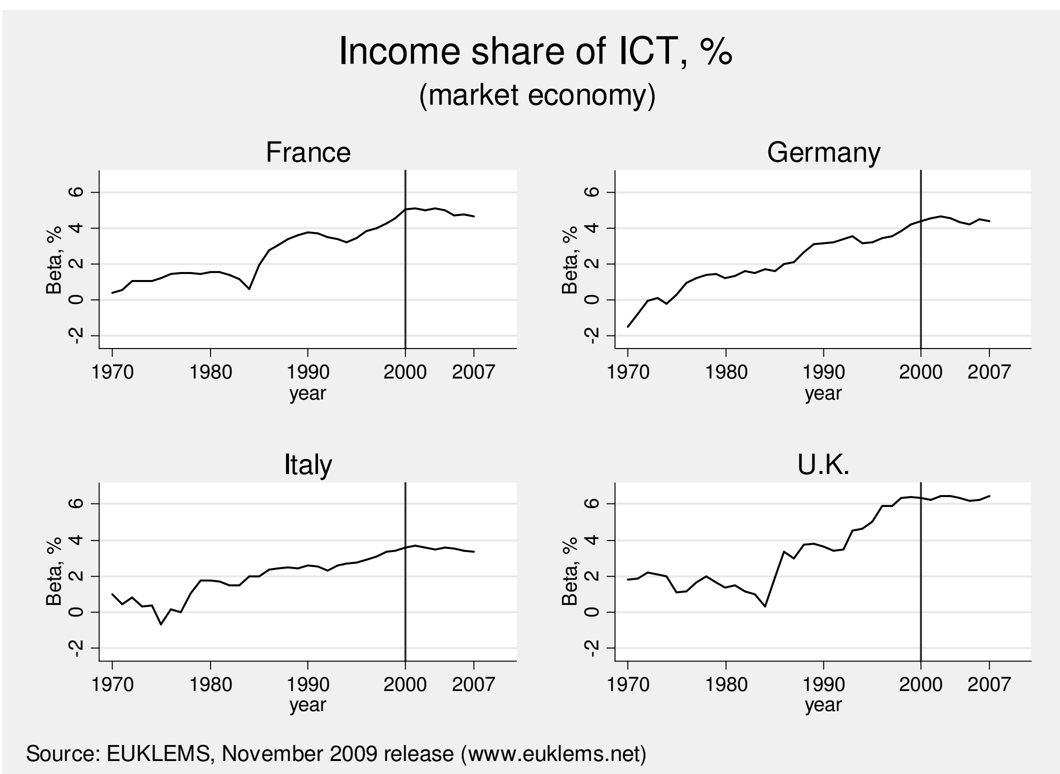
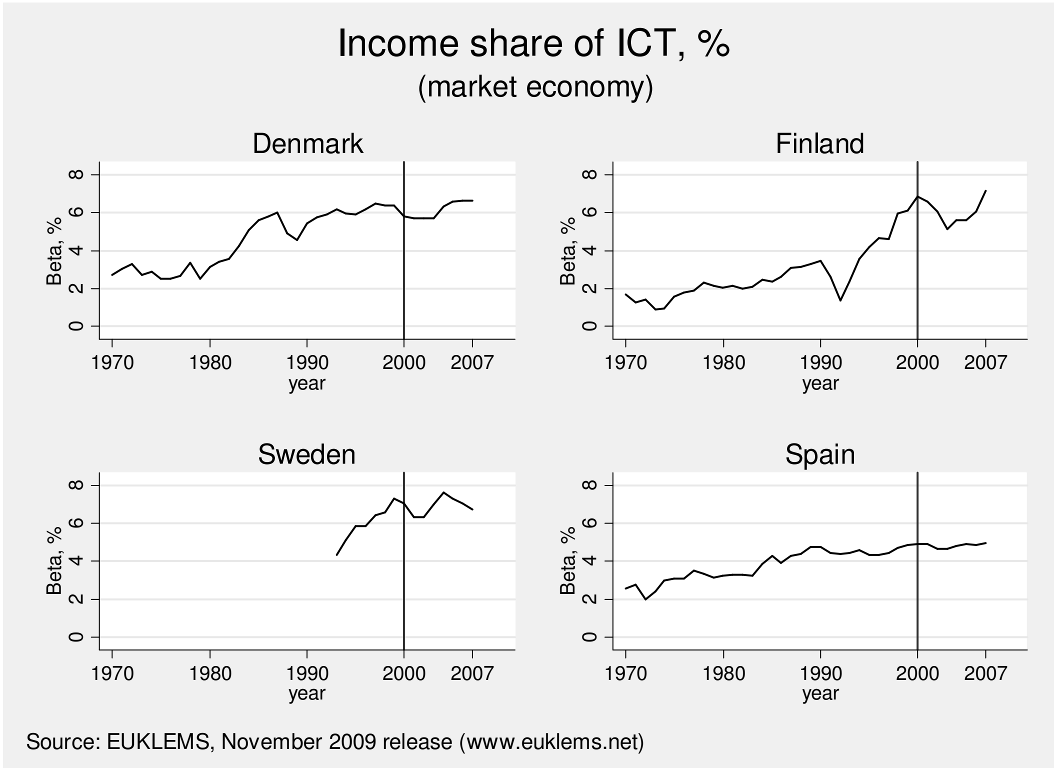


Chart 1, continued



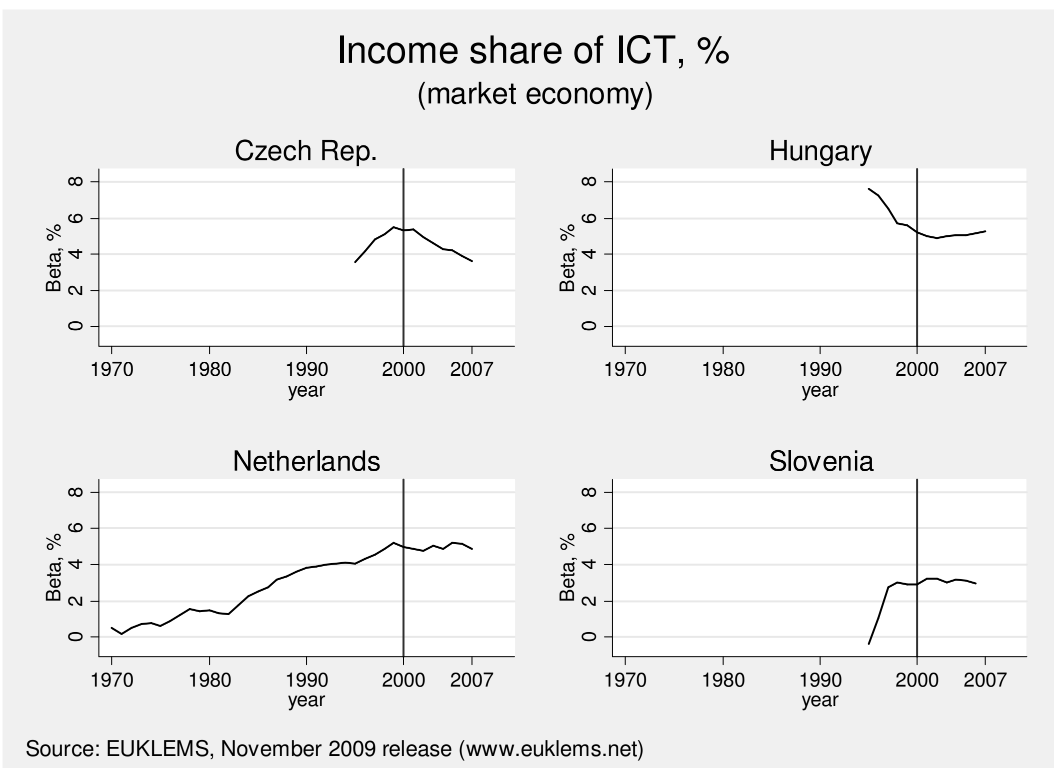


Chart 1, continued

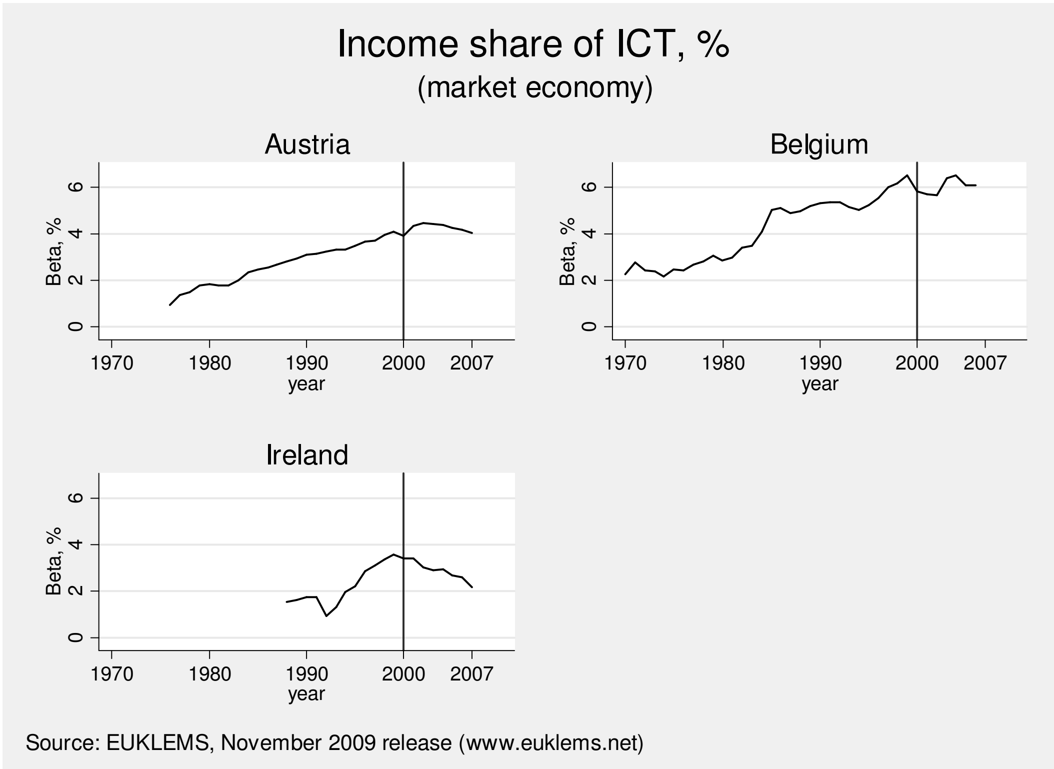
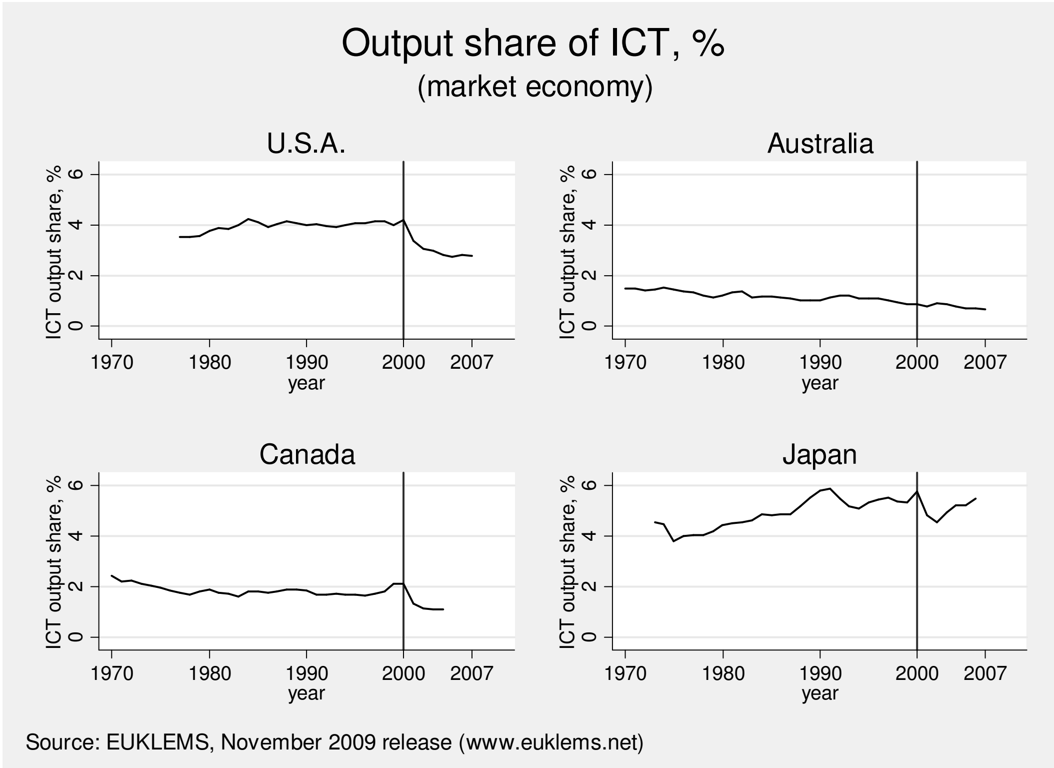


Chart 2
ICT output shares in the market economy, 19 countries, per cent (w_{ICT})



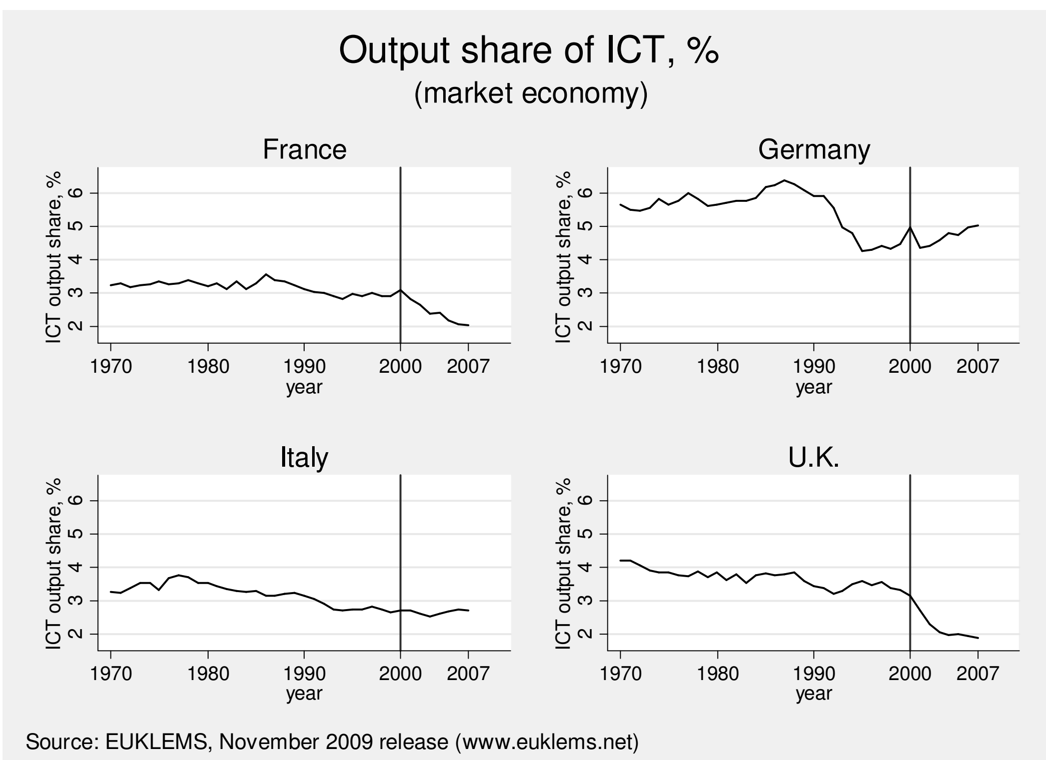
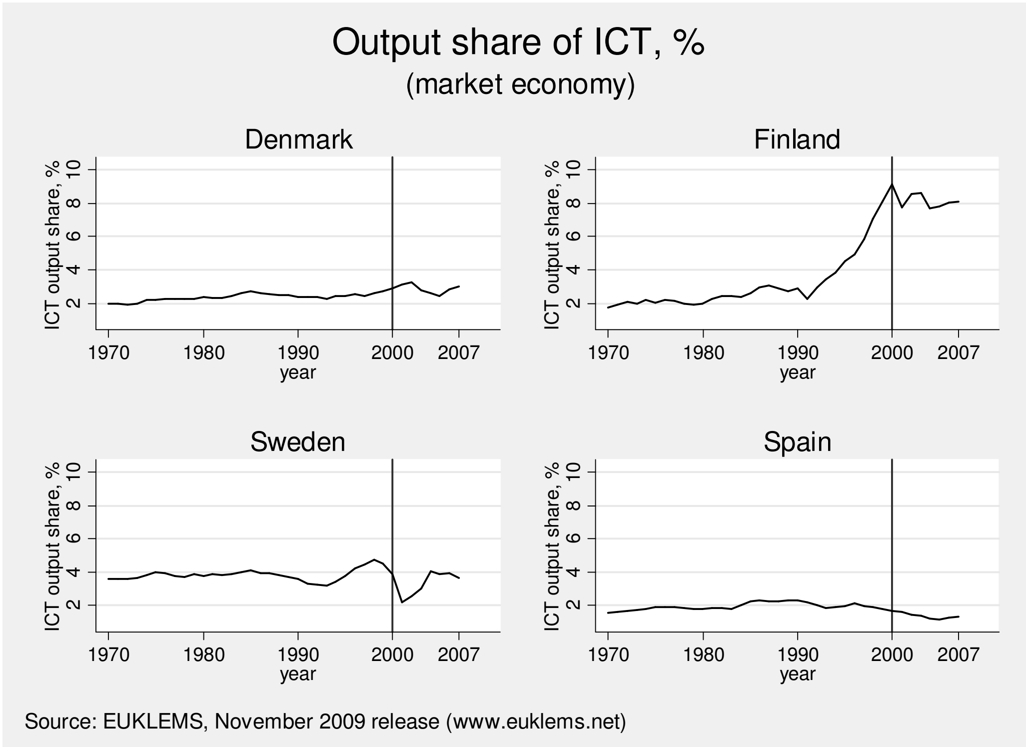


Chart 2, continued



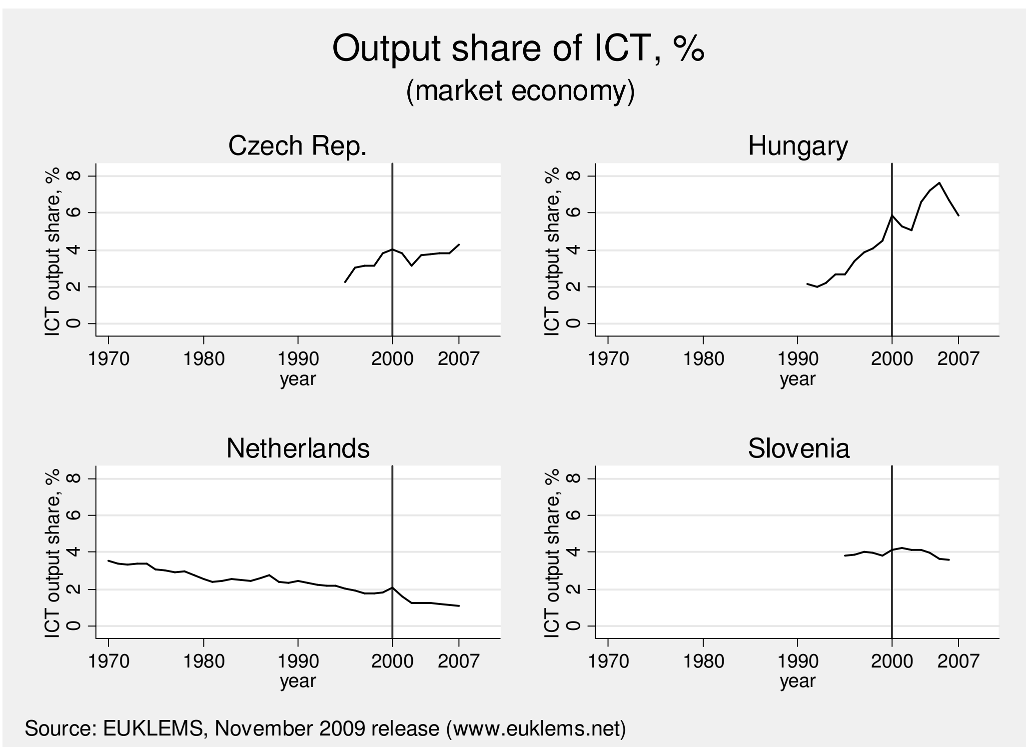


Chart 2, continued

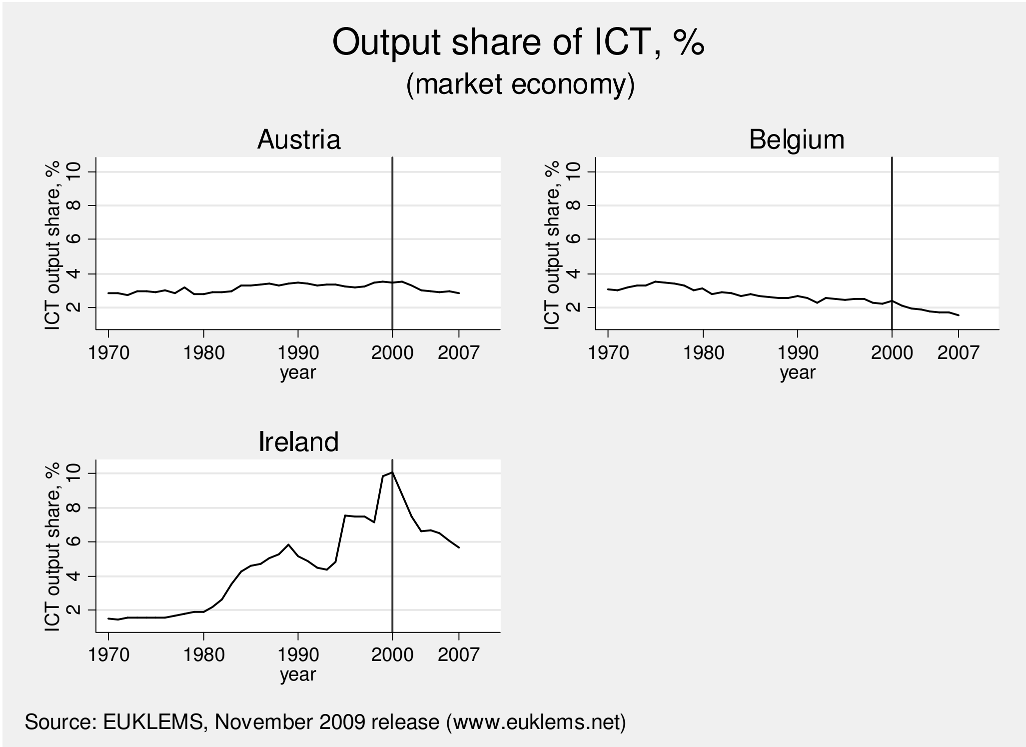


Chart 3
ICT income shares in the market economy (β), 19 countries, per cent

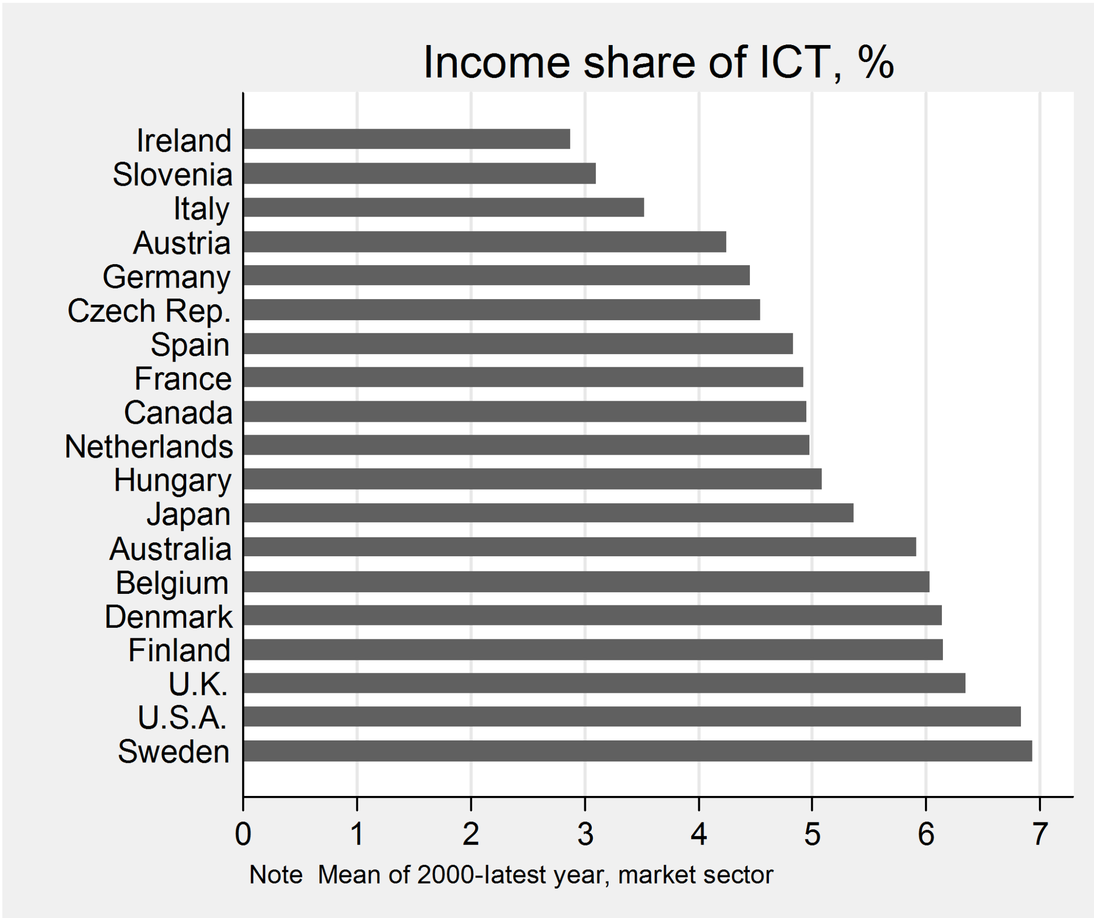


Chart 4
ICT output shares in the market economy (w_{ICT}), 19 countries, per cent

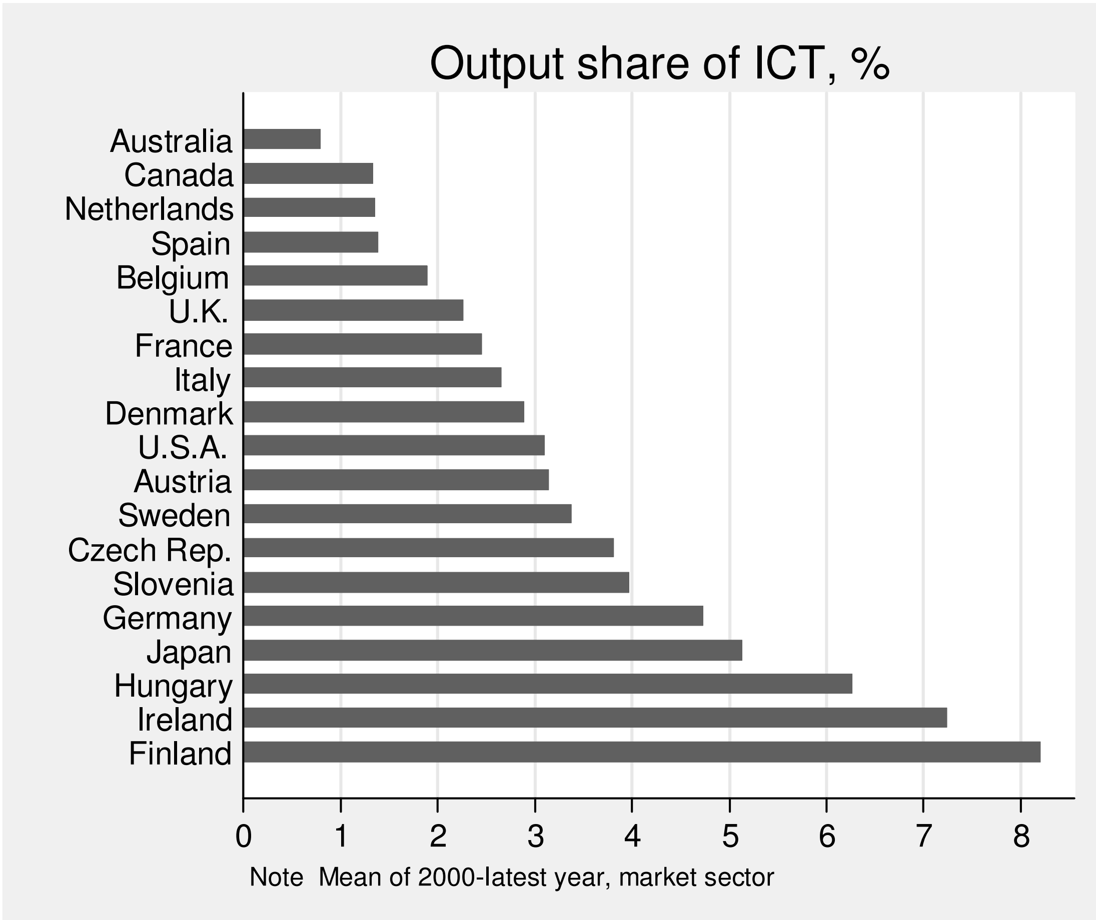
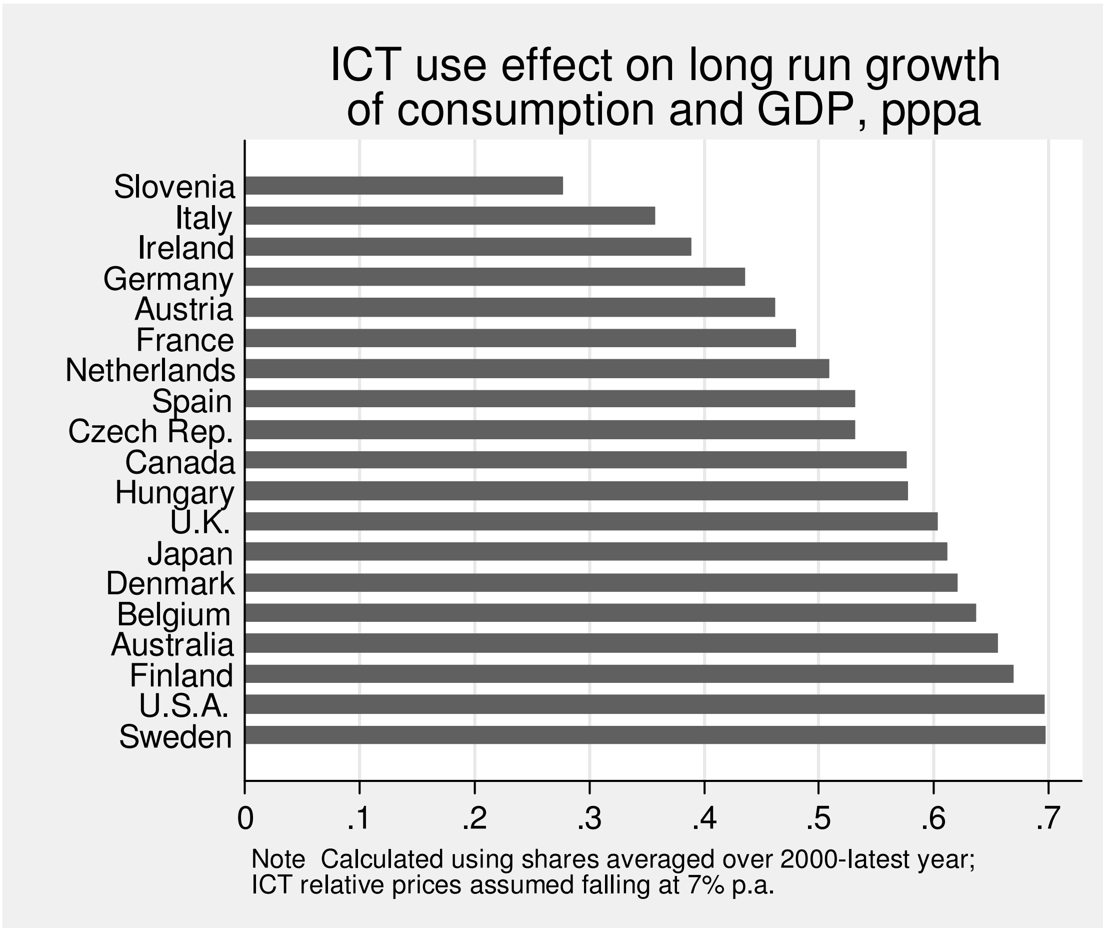


Chart 5



ICT use effect on long run growth
of consumption and GDP, pppa
Slovenia
Italy
Ireland
Germany
Austria
France
Netherlands
Spain
Czech Rep.
Canada
Hungary
U.K.
Japan
Denmark
Belgium
Australia
Finland
U.S.A.
Sweden
0
.1
.2
.3
.4
.5
.6
.7
Note Calculated using shares averaged over 2000-latest year;
ICT relative prices assumed falling at 7% p.a.

Chart 6

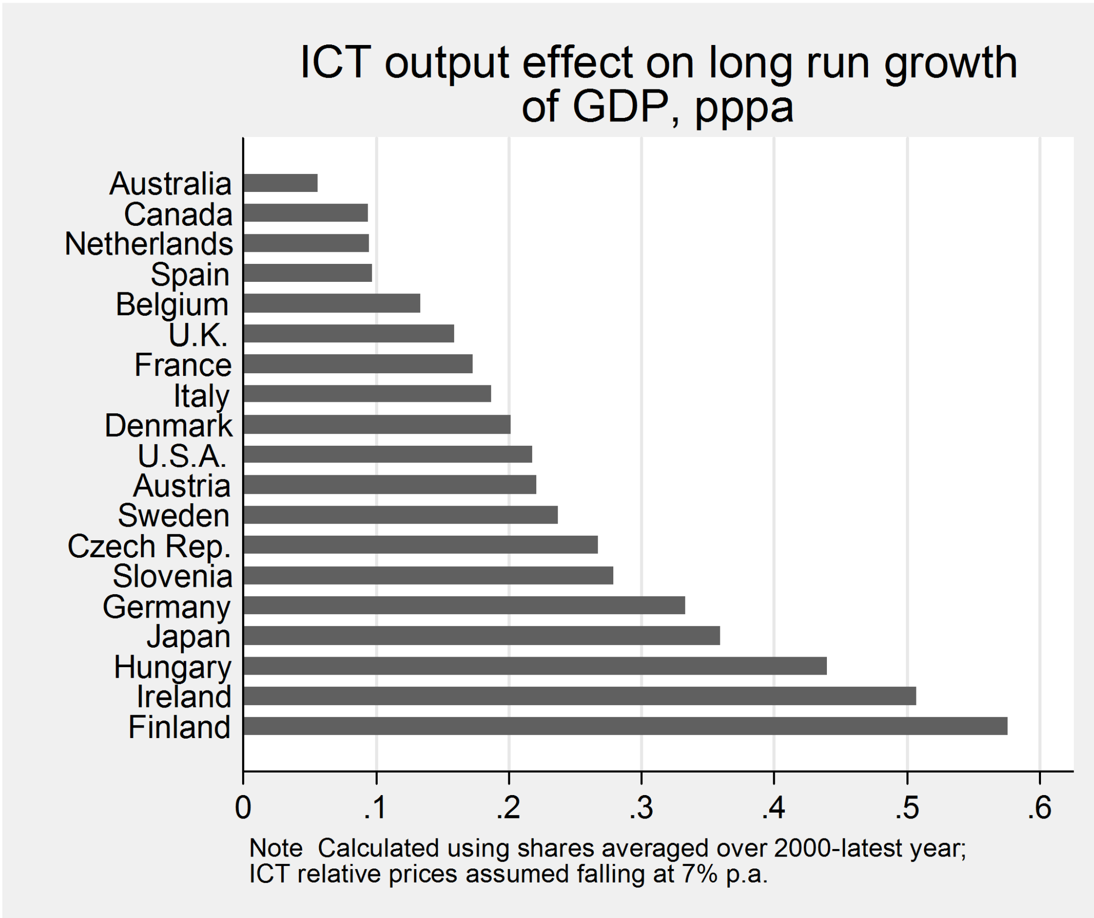

ICT output effect on long run growth of GDP, pppa
Australia
Canada
Netherlands
Spain
Belgium
U.K.
France
Italy
Denmark
U.S.A.
Austria
Sweden
Czech Rep.
Slovenia
Germany
Japan
Hungary
Ireland
Finland
0
.1
.2
.3
.4
.5
.6
Note Calculated using shares averaged over 2000-latest year;
ICT relative prices assumed falling at 7% p.a.

Chart 7

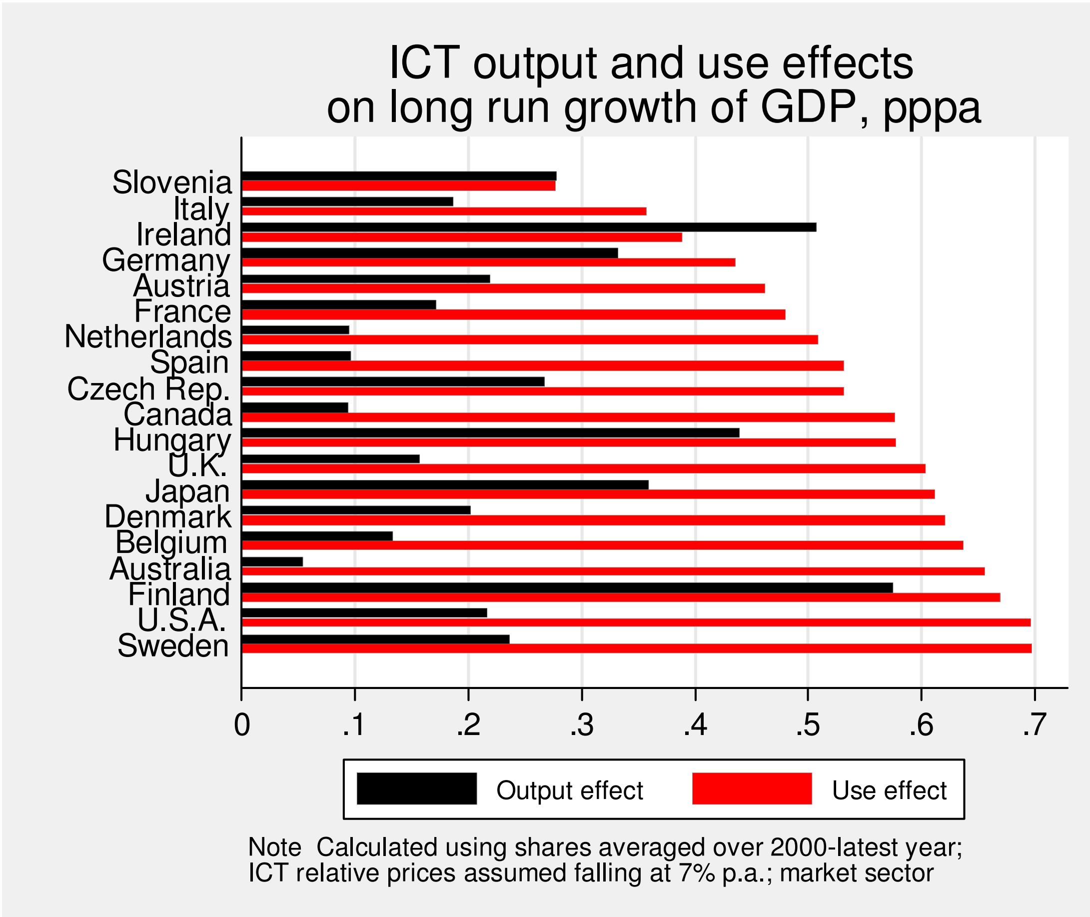
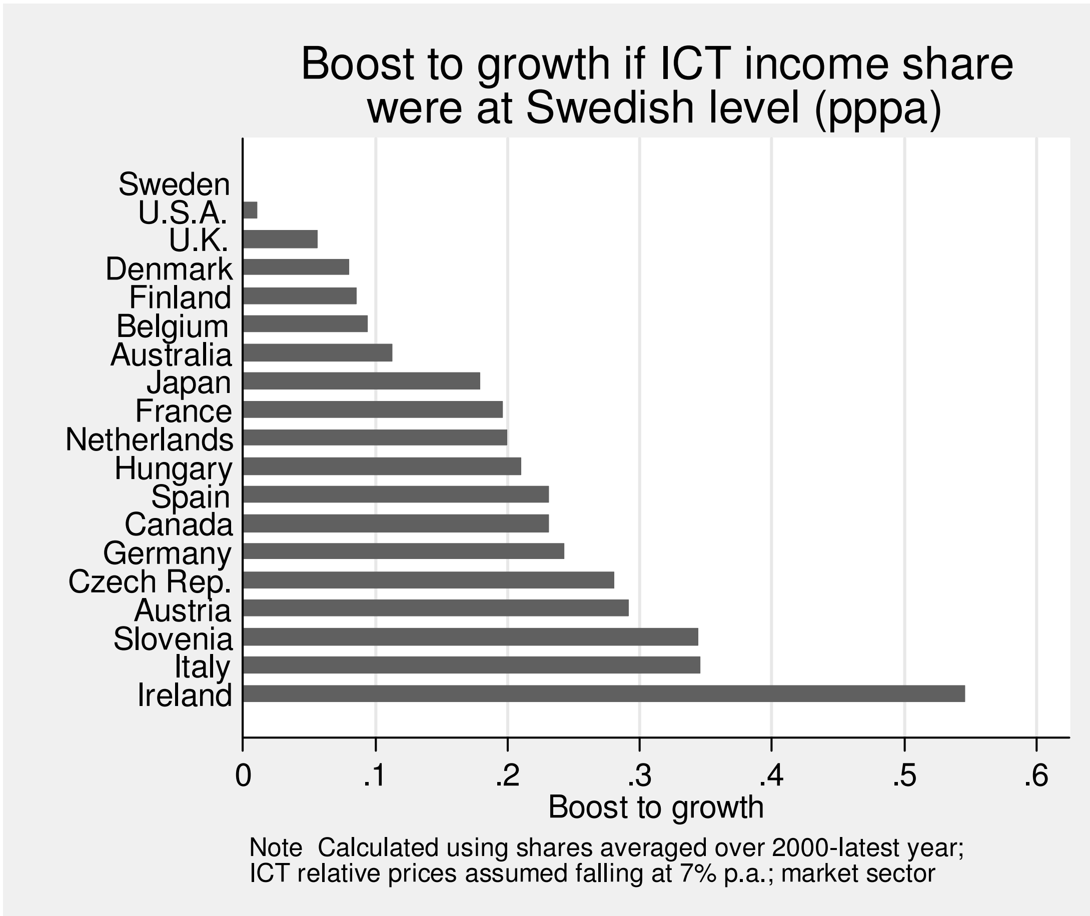

ICT output and use effects
on long run growth of GDP, pppa
Slovenia
Italy
Ireland
Germany
Austria
France
Netherlands
Spain
Czech Rep.
Canada
Hungary
U.K.
Japan
Denmark
Belgium
Australia
Finland
U.S.A.
Sweden
0
.1
.2
.3
.4
.5
.6
.7
Output effect
Use effect
Note Calculated using shares averaged over 2000-latest year;
ICT relative prices assumed falling at 7% p.a.; market sector

Chart 8


Boost to growth if ICT income share
were at Swedish level (pppa)
Sweden
U.S.A.
U.K.
Denmark
Finland
Belgium
Australia
Japan
France
Netherlands
Hungary
Spain
Canada
Germany
Czech Rep.
Austria
Slovenia
Italy
Ireland
0
.1
.2
.3
.4
.5
.6
Boost to growth
Note Calculated using shares averaged over 2000-latest year;
ICT relative prices assumed falling at 7% p.a.; market sector

ANNEX A
The steady state solution of the two-sector model

A.1 The model

This Annex sets out the open economy version of the two-sector model; the closed economy version then appears as a special case. As explained in the text, there are two sectors producing non-ICT and ICT goods respectively and perfect competition prevails in goods and factor markets. The equations of the two-sector model for a small open economy, which exports non-ICT products and imports ICT capital, are as given in the text and repeated here for convenience. First, the production functions for the two sectors which I assume are Cobb-Douglas and identical except for TFP:

$$y_C = \frac{Y_C}{H_C} = B_C h^{1-\alpha-\beta}\left(k_C^C\right)^{\alpha}\left(k_{ICT}^C\right)^{\beta} \qquad \text{(A1)}$$

$$y_{ICT} = \frac{Y_{ICT}}{H_{ICT}} = B_{ICT} h^{1-\alpha-\beta}\left(k_C^{ICT}\right)^{\alpha}\left(k_{ICT}^{ICT}\right)^{\beta} \qquad \text{(A2)}$$

where $k_i^j = K_i^j / H_j, \;\; i, j = C, ICT$ are the input intensities; *Y*, *B*, *h*, *K*, *H* denote output, TFP, skill level of a labour hour, capital and hours respectively. The growth rates of TFP in the two sectors are assumed exogenous.

Next, input supplies must equal demands:

$$K_C = K_C^C + K_C^{ICT} \qquad \text{(A3)}$$

$$K_{ICT} = K_{ICT}^C + K_{ICT}^{ICT} \qquad \text{(A4)}$$

$$H = H_C + H_{ICT} \qquad \text{(A5)}$$

Aggregate hours, *H*, are assumed exogenous. The accumulation equations, where *I* denotes investment and δ the depreciation rate, are:

$$\dot{K}_C = I_C - \delta_C K_C \qquad \text{(A6)}$$

$$\dot{K}_{ICT} = I_{ICT} - \delta_{ICT} K_{ICT} \qquad \text{(A7)}$$

and the supply-use balance equations are:

$$Y_C = C + I_C + X \qquad \text{(A8)}$$

$$Y_{ICT} = I_{ICT} - M \qquad \text{(A9)}$$

where X is the quantity of exports of non-ICT products and M is the quantity of imports of ICT capital goods.

Trade is assumed to be balanced in the steady state:

$$X^* = pM^* \tag{A10}$$

Here p is the price of ICT goods relative to that of consumption goods: $p = P_{ICT} / P_C$ where P_{ICT}, P_C are the nominal prices of the ICT and non-ICT goods.

A steady state is defined as constancy of the real interest rate and constancy of the proportions of aggregate hours allocated to each sector (see below). It will be shown that these conditions imply constancy of the steady state growth rate of consumption per aggregate hour worked.[16]

A.2 The growth rate of the relative price of ICT goods, *p*

Given our assumption that the production functions are the same up to a scalar multiple

[16] If the utility function takes the iso-elastic form, then constancy of the real interest rate implies constancy of the growth rate of consumption per hour worked and vice versa. Suppose the representative consumer has an inter-temporal utility function of the form $V(t) = \int_t^\infty u[c(s)]e^{-\rho(s-t)}ds,\ \rho > 0$, where the one-period utility function is iso-elastic: $u[c] = (c^{1-\theta} - 1)/(1-\theta)$ and c is consumption per hour worked, $c = C/H$. The consumer maximises $V(t)$ subject to the inter-temporal budget constraint that the present value of consumption cannot exceed initial wealth plus the present value of output of consumption goods: $\int_t^\infty c(s)e^{-(s-t)\int_s^\infty r(u)du}ds \le a(t) + \int_t^\infty [Y_C(s)/H(s)]e^{-(s-t)\int_s^\infty r(u)du}ds$, where $r(t)$ is the real rate of interest and $a(t)$ is assets per hour at time *t*. Then the first order condition states that $\dot{c}/c = (1/\theta)(r-\rho)$. So in this setup, if there exists a steady state in which consumption per hour grows at a constant rate, then in steady state the real interest rate r is constant too. Conversely, in an open economy the real interest rate may be taken as determined abroad, and if constant this implies a constant growth rate of consumption per hour. However the results here are not tied to any particular assumption about household saving behaviour or international capital markets.

(TFP), it is easy to see that

$$\hat{p} = \mu_C - \mu_{ICT} < 0 \tag{A11}$$

where $\mu_C = \hat{B}_C$ and $\mu_{ICT} = \hat{B}_{ICT}$, the TFP growth rates. This follows since we are assuming faster technical progress in ICT ($\mu_{ICT} > \mu_C$), i.e. the relative price of ICT goods is falling. The simplest way to prove this last result is to use the accounting identities that the value of output equals returns to the inputs:

$$P_i Y_i = R_C K_C^i + R_{ICT} K_{ICT}^i + WH_i, \quad i = C,\ ICT \tag{A12}$$

where P_C, P_{ICT} are the output prices, R_C, R_{ICT} are the nominal rental prices of capital, and W is the nominal hourly wage. Total differentiation of these equations with respect to time then yields the result that relative price growth equals relative TFP growth.[17]

A.3 The steady state growth rates of labour productivity

To find the steady state growth rates of labour productivity, first differentiate equation (A1) with respect to time. The growth rate of output per hour worked in the non-ICT sector is

$$\hat{y}_C = \mu_C + (1 - \alpha - \beta) g_h + \alpha \hat{k}_C^C + \beta \hat{k}_{ICT}^C \tag{A13}$$

where I have put $\mu_C = \hat{B}_C$ and a hat (^) denotes a growth rate. Next consider the marginal product of non-ICT capital in the consumption sector:

$$\frac{\partial Y_C}{\partial K_C^C} = \frac{\partial y_C}{\partial k_C^C} = \frac{\alpha y_C}{k_C^C} = \frac{\alpha Y_C}{K_C^C} \tag{A14}$$

The real user cost of holding a unit of non-ICT capital in the consumption sector is given by $r + \delta_C$ where r is the real rate of return (in terms of consumption goods) and δ_C is the depreciation rate on non-ICT capital. Profit-maximisation requires that the real user cost equal the real marginal product of non-ICT capital:

$$r + \delta_C = \frac{\alpha y_C}{k_C^C} \tag{A15}$$

[17] This derivation uses the fact that the share of a given input is the same in both sectors (a) because competition ensures that its price is the same in both sectors and (b) because the input intensity is the same due to the assumption that the production functions are identical up to a scalar multiple.

Consider now a steady state where the real interest rate is constant. Since the left hand side of this last equation is constant, so too must be the right hand side, i.e.

$$\hat{y}_C^* = \hat{k}_C^{C*} \tag{A16}$$

where a star (*) denotes the steady state. Now consider ICT capital employed in the consumption sector. According to the Hall-Jorgenson formula (abstracting from tax for simplicity), the real user cost of ICT capital is:

$$[r + \delta_{ICT} - (\hat{P}_{ICT} - \hat{P}_C)](P_{ICT} / P_C) = [r + \delta_{ICT} - \hat{p}]p$$

and the real interest rate is the nominal interest rate minus the growth rate of the price of consumption. Once again, the real user cost of capital must equal the marginal product:

$$[r + \delta_{ICT} - \hat{p}]p = \beta \frac{y_C}{k_{ICT}^C} \tag{A17}$$

Consider again the steady state. We expect r and also $\hat{p}$ to be constant (see below), but the relative price p itself is falling. So the left hand side is falling at rate $\hat{p}$. Hence the right hand side must be falling at the same rate, i.e.

$$\hat{y}_C^* - \hat{k}_{ICT}^{C*} = \hat{p} \tag{A18}$$

Substituting equations (A16) and (A18) into (A13), we obtain:

$$\begin{aligned} \hat{y}_C^* &= \mu_C + (1-\alpha-\beta)g_h + \alpha \hat{y}_C^* + \beta(\hat{y}_C^* - \hat{p}) \\ &= \frac{\mu_C - \beta\hat{p}}{1-\alpha-\beta} + g_h \end{aligned} \tag{A19}$$

Analogously, note that the equality of the real marginal product of ICT capital in ICT production with its real user cost implies that

$$[r + \delta_{ICT} - \hat{p}] = \beta \frac{y_{ICT}}{k_{ICT}^{ICT}} = \beta \frac{Y_{ICT}}{K_{ICT}^{ICT}} \tag{A20}$$

Since the left hand side of equation (A20) is constant in steady state, we have

$$\hat{y}_{ICT}^* = \hat{k}_{ICT}^* \tag{A21}$$

It then also follows from (A18) that

$$\hat{y}^*_{ICT} = \hat{y}^*_C - \hat{p}$$

$$= \frac{\mu_C - \beta\hat{p}}{1-\alpha-\beta} + g_h - \hat{p} \qquad \text{(A22)}$$

$$= \frac{\mu_C - (1-\alpha)\hat{p}}{1-\alpha-\beta} + g_h$$

Equations (A19) and (A22) are the solutions for the steady state growth rates of labour productivity.

A.4 The steady state growth rates of output

From (A16) and (A21) we have

$$\hat{Y}^*_C = \hat{K}^{C*}_C \qquad \text{(A23)}$$

$$\hat{Y}^*_{ICT} = \hat{K}^{ICT*}_{ICT} \qquad \text{(A24)}$$

and from (A18)

$$\hat{Y}^*_C = \hat{K}^{C*}_{ICT} + \hat{p} \qquad \text{(A25)}$$

The equality of the real marginal product of *non*-ICT capital in ICT production with its real user cost implies that

$$\frac{r+\delta_C}{p} = \alpha\frac{y_{ICT}}{k^{ICT}_C} = \alpha\frac{Y_{ICT}}{K^{ICT}_C} \qquad \text{(A26)}$$

whence

$$\hat{Y}^*_{ICT} = \hat{K}^{ICT*}_C - \hat{p} \qquad \text{(A27)}$$

These results are not sufficient by themselves to pin down the growth rates of output. But we can do so by recognising that a steady state requires that the allocation of labour between the two sectors be constant, which implies that $\hat{H}^*_C = \hat{H}^*_{ICT} = \hat{H}$. The reason is that a rise in the share of aggregate hours devoted to (say) the consumption sector is not sustainable: it must come to an end, if only because the share cannot exceed one (when the economy is completely specialised). I therefore require the allocation of labour to be constant in steady state. Now if $\hat{H}^*_C = \hat{H}^*_{ICT} = \hat{H}$, then $\hat{K}^{C*}_C = \hat{K}^{ICT*}_C = \hat{K}^*_C$ and $\hat{K}^{C*}_{ICT} = \hat{K}^{ICT*}_{ICT} = \hat{K}^*_{ICT}$ since the input intensities must be the same in both sectors. We have then

$$\hat{Y}_C^* = \hat{y}_C^* + \hat{H} \tag{A28}$$

(since $\hat{y}_C^* = \hat{Y}_C^* - \hat{H}_C^*$) where $\hat{y}_C^*$ is given by (A19), and by subtracting (A24) from (A23)

$$\hat{Y}_{ICT}^* = \hat{Y}_C^* - \hat{p} > \hat{Y}_C^* \tag{A29}$$

Since the stocks of each type of capital are growing at the same rate in each sector, then from (A23) and (A24)

$$\hat{K}_C^* = \hat{I}_C^* = \hat{Y}_C^* \tag{A30}$$

$$\hat{K}_{ICT}^* = \hat{I}_{ICT}^* = \hat{Y}_{ICT}^* \tag{A31}$$

The growth rates of exports and imports come from (A9) and (A10):

$$\hat{M}^* = \hat{Y}_{ICT}^* \tag{A32}$$

$$\hat{X}^* = \hat{M}^* + \hat{p} = Y_{ICT}^* + p = Y_C^* \tag{A33}$$

using (A29).

Equations (A28)-(A33) are therefore the solutions for the steady state growth rates of the outputs, capital stocks, investment, exports and imports.

A.5 The steady state growth rate of consumption

We are now in a position to derive the steady state solution for consumption. By totally differentiating (A8) with respect to time, we find that

$$\hat{Y}_C = \left(\frac{C}{Y}\right)\hat{C} + \left(\frac{I_C}{Y}\right)\hat{I}_C + \left(\frac{X}{Y}\right)\hat{X}$$

Plugging in the steady state growth rates for I_C and *X*, the solution for consumption is

$$\hat{C}^* = \hat{Y}_C^*$$

And the solution for the growth rate of consumption per hour ($c = C / H$) is, using (A19),

$$\hat{c}^* = \frac{\mu_C - \beta\hat{p}}{1-\alpha-\beta} + g_h \tag{A34}$$

The existence of a steady state growth rate of consumption is therefore a consequence of the requirements that the real interest rate and the allocation of labour are constant.

A.6 Shares

These results on growth rates enable us to show that the following ratios are constant in steady state:

$$\begin{aligned}
\text{Investment shares (in value terms)}: &\quad I_C^* / (Y_C^* + pY_{ICT}^*),\ pI_{ICT}^* / (Y_C^* + pY_{ICT}^*) \\
\text{Saving ratio (in value terms)}: &\quad (I_C^* + pI_{ICT}^*) / (Y_C^* + pY_{ICT}^*) \\
\text{Capital} - \text{output ratio (in value terms)}: &\quad (K_C^* + pK_{ICT}^*) / (Y_C^* + pY_{ICT}^*) \\
\text{Income shares of non-ICT capital, ICT capital, and labour}: &\quad \alpha,\ \beta,\ 1-\alpha-\beta \\
\text{Shares in value of output}: &\quad Y_C^* / (Y_C^* + pY_{ICT}^*),\ pY_{ICT}^* / (Y_C^* + pY_{ICT}^*) \\
\text{Shares of labour force}: &\quad H_C^* / H,\ H_{ICT}^* / H
\end{aligned}$$

It is not possible to solve for the steady state *levels* of the outputs and consumption without introducing more structure, e.g. household saving behaviour. However, levels are not required for the projections in the text.

The closed economy is a special case of the open economy model in which exports and imports are always zero. It can be seen that this does not affect the steady state solutions for the growth rates of output, capital and consumption. Another special case is where the economy is open but completely specialised on the production of the consumption good. Again, this has no effect on the solution for the growth rate of consumption. Finally, the model can be adapted to a third case where the economy is an ICT exporter: just replace X by $-M$ and vice versa in equations (A8) and (A9). Once again, the solution for the growth rate of consumption is unchanged.

ANNEX B

Does the one-sector model fit the facts?

I evaluate the adequacy of the one-sector model by seeing how well it can explain past growth in the U.K. The parameter values to be used in evaluating the model are derived from a growth accounting analysis.

Table B1 gives a growth accounting decomposition for the U.K. market sector over 1979-2003, based on 31 market sector industries in the Bank of England Industry Dataset (BEID).[18] The growth of labour productivity (output per hour) is explained by capital deepening (the growth of capital services weighted by the share of capital in GDP), the contribution of labour quality (an index of the growth of human skill per hour weighted by labour's share in output), by reallocation, and by TFP (the residual). Capital deepening is also broken down into ICT capital deepening and non-ICT capital deepening.[19] Capital deepening explains around 70% of the growth of labour productivity in our period (1979-2003). Next in importance comes labour quality and close behind is TFP. Since 1990, the growth rate of labour productivity has declined somewhat. The growth rate of TFP rose in the first half of the 1990s, declined in the second half, and then recovered in the first three years of the new century. The importance of ICT capital is clear: since 1979, it has accounted for about half of all capital deepening, despite the fact that even in 2003 ICT capital is only 8% of all fixed capital in the market sector. Its relative and absolute importance fell in the first half of the 1990s, then rose sharply in the second half. In 1995-2000 ICT capital deepening accounted for 61% of the growth of labour productivity. Its importance has fallen somewhat since 2000 but it still accounts for 38% of productivity growth, more than at any other time except 1995-2000.

To evaluate the one-sector model, I assume initially that the U.K. economy was in steady

[18] I start in 1979 rather than 1970 for two reasons. First it was a cyclical peak. Second, the ICT data are less reliable for the 1970s.

[19] These results are based on those reported by Oulton and Srinivasan (2005, Table 6.1) but revised and updated. The main reason is that the whole economy hours series (ONS code: YBUS) has been heavily revised. This series derives from the Labour Force Survey and the grossed-up results from the latter were revised following the 2001 Census of Population which initially found one million fewer people than had been expected.

state, at least on average, over the period 1979-2003: Chart B1, panel (a) suggests that this assumption does not do too much violence to the data. So we start by computing what the growth rate would have been under this assumption. To do this we need to know the mean growth rate of TFP, the mean growth rate of skill, and the mean labour share: see equation (5). The growth rate of TFP in the market sector was 0.54 per cent per year over this period, the share of labour averaged 0.581, while the growth rate of skill averaged 0.71 per cent per year (see Table B1). With these parameter values, the steady state growth rate is 2.00 per cent per year. But in fact output per hour grew at 2.76 per cent per year over 1979-2003 (see Table B1 again). So the one-sector model, if applied to the past and assuming a steady state, would have grossly understated the actual outturn. If applied to the future, the one-sector model would imply a massive slowdown in growth, by three quarters of a percentage point, below the average rate of the recent past.

The one-sector model might be reconcilable with the data if we assumed that the economy was initially below its steady state path. Then capital would be predicted to grow more rapidly than in steady state, as indeed it did, thus allowing output also to grow more rapidly than in steady state. Though it might be possible to fit past data better this way, the one-sector model would continue to imply a slowdown in future growth. This approach can be tested by estimating steady state output per hour and comparing it with the actual level. The solution for steady state output per hour is:

$$y(t)^* = \left[B(t)h(t)\right]^{1/(1-\alpha)} \left[\frac{s}{n + g_h + \frac{\mu}{1-\alpha} + \delta}\right]^{\alpha/(1-\alpha)} \qquad \text{(B1)}$$

where s is the ratio of investment to output, g_h is the growth rate of skill, and $B(t)h(t) = B(0)\exp(g_h + \frac{\mu}{1-\alpha})$, with the normalisation $h(0) = 1$.[20] We can use this equation to estimate the level of steady state output per hour in the sample period and compare it with the actual path. The ratio of actual to steady state output per hour is given in Chart B1, panel (b).

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[20] The unknowns in equation (B1) can be quantified as follows. From the production function, equation (1), we can find that $B(0) = Y(0)^{1/(1-\alpha)} K(0)^{-\alpha/(1-\alpha)}$, employing the further normalisation $H(0) = 1$. In addition to the parameters already employed, we now need to know also the growth of hours (n), the depreciation rate (δ), and the investment ratio (s). The growth of hours worked was close to zero at -0.08% per year (Table B1). The depreciation rate (δ) was fairly constant and trendless, averaging 8.40%. The investment ratio (s) was similarly trendless, averaging 16.54%.

This shows that output per hour was initially about 15% below the steady state level, but catches up with it by 1985. However, after that it continues growing above the steady state rate. This is of course inconsistent with the one-sector model, which should show growth slowing down as the steady state is approached.

Actually, we can be more precise than this. If the production function is Cobb-Douglas and the savings rate is constant (as we have seen was approximately true), then there is a closed form solution for the growth rate of output per hour in the one-sector model (Barro and Sala-i-Martin, 1995, chapter 1, page 53). In our notation this can be written as:

$$\hat{y} = \frac{\mu}{1-\alpha} + g_h + \alpha\left(n + g_h + \frac{\mu}{1-\alpha} + \delta\right)\left[\left(\frac{y(t)}{y(t)^*}\right)^{-\alpha/(1-\alpha)} - 1\right] \quad \text{(B2)}$$

This equation can be written in discrete form as:

$$\ln\left[\frac{y_t}{y_{t-1}}\right] = \frac{\mu}{1-\alpha} + g_h + \alpha\left(n + g_h + \frac{\mu}{1-\alpha} + \delta\right)\left[\left(\frac{y_{t-1}}{y_{t-1}^*}\right)^{-\alpha/(1-\alpha)} - 1\right] \quad \text{(B3)}$$

We can employ this last equation together with equation (B1) to generate the growth path predicted by the one-sector model for the U.K. economy to compare with the actual path over 1970-2003: see Chart B1, panel (c). This shows that the one-sector model continues to under-predict the actual growth rate experienced over this period and that the discrepancy grows over time. So the conclusion is that, whether or not we assume the economy was in a steady state, we cannot get the one-sector model to fit the data.

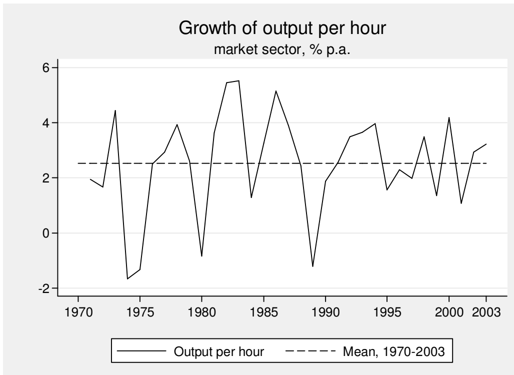
Table B1
Labour productivity growth in the market sector of the U.K. economy: a growth accounting decomposition

	1979-2003	*1979-1990*	*1990-1995*	*1995-2000*	*2000-2003*
Growth rates, % p.a.					
Output per hour (LP)	2.76	2.77	3.04	2.66	2.41
Hours	-0.08	0.07	-1.47	1.07	-0.20
Contributions to LP growth, % p.a.					
Capital deepening	1.93	2.01	1.63	2.25	1.65
ICT	*0.99*	*0.86*	*0.67*	*1.62*	*0.91*
Non-ICT	*0.95*	*1.14*	*0.95*	*0.62*	*0.75*
Skill	0.42	0.37	0.70	0.36	0.20
Reallocation	-0.13	-0.12	-0.16	-0.11	-0.17
TFP	0.54	0.51	0.88	0.17	0.72
Shares in LP growth, %					
Capital deepening	70.1	72.5	53.5	84.5	68.7
ICT	*35.8*	*31.2*	*22.1*	*61.0*	*37.6*
Non-ICT	*34.3*	*41.2*	*31.4*	*23.5*	*31.1*
Skill	15.1	13.5	23.0	13.4	8.3
TFP	14.8	14.1	23.5	2.1	22.9
Memo items					
Income share of labour, %	58.1	58.6	57.9	56.7	58.5
Growth of capital services per hour, % p.a.	4.63	4.88	3.92	5.18	3.99
Growth of skill, % p.a.	0.71	0.63	1.19	0.63	0.72

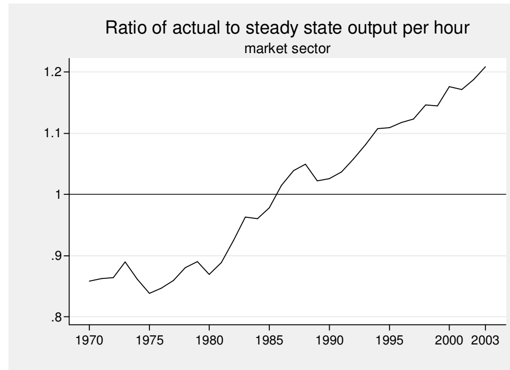
Source A revised version of results in Oulton and Srinivasan (2005). Data are from Bank of England Industry Dataset, version 3. Growth of output per hour is the sum of the contributions from capital, labour quality, reallocation and TFP. For details of sources and methods, see Oulton and Srinivasan (2005).

Chart B1
How well does the one-sector model fit the U.K. economy?

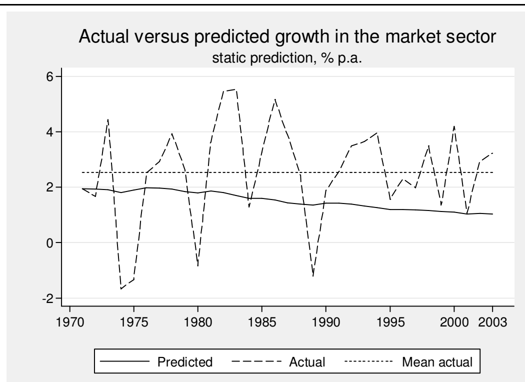
(a)



(b)



(c)



Source: Own calculations (see text), using data from Table B1.

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