ICT and Productivity Resurgence: a growth model for the Information Age

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Abstract

Since the mid-1990s, extraordinary advances in semiconductors have enhanced the embodied nature of information technology, fuelling efficiency growth in computers and communication equipment industries. The consequent fall in prices has enabled the rapid diffusion of these new technologies, which have then reached the critical threshold to foster productivity growth.
In light of the recent growth pattern of the United States, this paper presents a model where the endogenous engine of development is the learning-by-doing process stemming from the usage of ICT for investment and consumption. Based on a two-sector framework (à la Whelan) that distinguishes between ICT-producers and -users, the model yields a sound representation of the stylized facts of the Information Age.

Keywords: information technology, learning-by-doing, productivity resurgence.
JEL: E21, E22, O41.

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1 Introduction

In the mid-1990s the United States entered what is often called the Information Age. After a long period of sluggishness, labour productivity shifted to a high growth regime. A crucial contribution to the American resurgence has been made by information and communication technology (ICT). As a result of extraordinary advances in semiconductor technology, a wide array of goods embodying such intermediate inputs (computers, communication equipment, etc.) has become more efficient and cheaper, spreading rapidly throughout the economy. ICT capital deepening and TFP growth in ICT-producing industries account for a large proportion of the recent acceleration in GDP per hour worked, dispelling any residual doubts about the growth effect of information technology.[1]

The aim of this paper is to propose a growth model able to represent the stylized facts of the Information Age. Drawing on the empirical literature, it considers a multi-sector economy that distinguishes between ICT producers and users. The engine of economic growth is identified as the learning-by-doing which comes about in both the productive and home utilization of ICT. A distinctive property of these new technologies, in fact, is that they have revolutionized both business practices and household life. Information technology has enormously facilitated the circulation of ideas and access to knowledge, thereby enlarging growth opportunities.

The paper is structured as follows. Section 2 describes the sources and dynamics of the productivity revival recently experienced by the United States. Section 3 sets out the model and shows the conditions under which it fits the US growth pattern of the last decade. Section 4 discusses the model's architecture and results, showing how it relates to the existing literature. Finally, Section 5 makes some concluding remarks.

2 ICT and Productivity Resurgence: some stylized facts

The resurgence of American growth since the mid-1990s has been due to the rapid acceleration of labour productivity. Relatively to the *slowdown age* (1973-95), the annual growth rate of GDP per hour worked doubled after 1995 (from 1.47 to 2.86%; see Table 1), even outpacing the *golden rates* of the pre-oil crises period.

There is now a broad consensus that a profound change occurred in the

[1]See for instance Gordon (2003).

fundamentals of the US economy, and that it was driven by ICT. Around 1994-95, the changeover from a three- to a two-year product cycle delivered huge efficiency gains and price reductions in the semiconductors industry: around 90% per year according to Jorgenson (2001). The stellar improvement in the price-performance ratio of technologically advanced intermediate inputs rapidly transferred to the final producers of ICT; the consequent fall in relative prices enabled the massive deployment of computers and communication equipment by firms and households. The miniaturization of microelectronic components enhanced the embodied nature of information technology, making new vintages of ICT capital goods extremely more powerful, more efficient and cheaper. For this reason, semiconductors are considered the inner general purpose technology (GPT) at the basis of the Information Age.[2]

The breakdown of labour productivity growth in Table 1 highlights the lion part played by information technology in the US resurgence. ICT capital deepening is the main contributor to average hourly productivity in most recent years (*adoption effect*), being well above traditional assets (0.86 against of 0.66%-points). Moreover, disentangling the aggregate growth of total factory productivity into the industry sources shows how ICT producers directly contributed another half of a percentage point to the annual growth of GDP per hour worked (*production effect*). This finding is highly significant in light of the small size of the ICT sector (which represents less than 5% of the total economy). On the whole, considering both the adoption and the production effects, information technology accounts for nearly fifty percent of aggregate labour productivity growth in the period 1995-2002 (1.33 over 2.86%) and much more in terms of its contribution to the acceleration after 1995 (0.76 over 1.39%).

Moving to the consumption side, Jorgenson and Stiroh (2000) stress that household purchases of computers have parallelled the uptake of firms since the second half of the last decade; indeed, the increasing use of the Internet, laptops and mobile phones has revolutionized how consumers manage their activities and spare time. In this regard, Venturini (2006) estimates that the growth contribution of computer consumption is even larger than that of investment in communication equipment and software in the US as well as in most EU countries. Moreover, the output growth gap between Europe and the United States since the mid-1990s has largely depended on the differentials in ICT expenditure by businesses and consumers. According to Jovanovich and Rousseau (2005), it is because of the extent to which ICT

[2]Given their pervasive use in a wide range of sectors and technical dynamism, semiconductors are comparable to the most important inventions of the past (Bresnahan and Trajtenberg, 1995, p. 84).

Table 1: **Sources of labor productivity growth in the United States**, 1948-2002 (average annual percentage rates of growth)

	1948 - 1973	**1973 - 1995**	**1995 - 2002**	**1995-2002 less 1973-95**
Average Labour Productivity (ALP)	**2.72**	**1.47**	**2.86**	**1.39**
Contribution of Capital Deepening:	**1.49**	**0.83**	**1.52**	**0.69**
ICT capital	0.14	0.36	0.86	0.50
Non-ICT capital	1.35	0.47	0.66	0.19
Contribution of Labour Quality	**0.43**	**0.27**	**0.20**	**-0.07**
Total Factor Productivity:	**0.80**	**0.37**	**1.14**	**0.77**
ICT producing industries	0.05	0.21	0.47	0.26
Non-ICT producing industries	0.75	0.16	0.67	0.51
Total ICT contribution to ALP growth *(ICT capital deepening+TFP growth of ICT producers)*	**0.19**	**0.57**	**1.33**	**0.76**

Source: Own calculations on Jorgenson (2005). Each contribution is an income share-weighted growth rate.

has transformed both household life and business practices that it can be regarded as a GPT. Drawing a close comparison between the electrification and digitalization of the US economy, Jovanovich and Rousseau (2005) show that ICT is superior in terms of innovation spawning and quality improvement over time. Whereas information technology diffused less rapidly across industries, especially in the first period after its advent, home adoption of computers has been indubitably faster than electricity. Learning costs are the main constraints on its spread; however, these are progressively decreasing, given the rise in the average level of human capital.

3 The model

Structure of the economy and production technology. In order to model the above describe stylized facts let us consider a two-final sector, closed economy *à la* Whelan (2003), where the production functions are of the Cobb-Douglas type characterized by identical factor proportions but different Hicks-neutral technology. There is perfect competition and constant returns to scale in each sector and α is the labour share on income, $\alpha \in]0, 1[$.

The traditional (non-durable) sector is assumed to produce only consumption goods; in so doing, it utilizes labour input (l_{1t}) and ICT assets manufactured by the innovative (durable) industry (k_{1t}):

$$c_{1t} = z_{1t} k_{1t}^{1-\alpha} l_{1t}^{\alpha}. \tag{1}$$

On the other side, the output of the durable sector produced with ICT capital (k_{2t}) and labour (l_{2t}) can either be used as capital goods by firms (i_t) or consumed by households (c_{2t}):

$$c_{2t} + i_t = y_{2t} = z_{2t} k_{2t}^{1-\alpha} l_{2t}^{\alpha}. \tag{2}$$

In what follows, the former industry will be referred to as *ICT-user*, the latter as *ICT-producer*.

Factor inputs are always fully employed in this economy, being perfectly mobile across industries. Normalizing the exogenous labor supply to one, we simply set $l_{1t} = l_t$ and $l_{2t} = 1 - l_t$, so as to have $l_{1t} + l_{2t} = 1$ and $k_t = k_{1t} + k_{2t}$. Households own firms and allocate labour and capital between the two sectors by means of the shares l_t and θ_t (both $\in]0, 1[$), where θ_t is the fraction of ICT capital stock utilized by ICT-producing industry ($k_{2t} = \theta_t k_t$). Since there are no demographic dynamics, any variable of the system is expressed in effective units; therefore, y_{it} denotes industry labour productivity, while c_{it}, i_t and k_{it} are respectively per capita consumption, investment and capital stock.

ICT goods show a qualitative improvement relatively to the older vintages because they incorporate more efficient semiconductors over time. In a framework like this one, based on final productions, the improved quality of new capital assets can be modelled only implicitly by including an efficiency index of the technologically advanced intermediate productions (q_t). q_t converts the flow of new durable (ICT) goods into quality-constant units and represents the embodiment process featuring the advancement in information technology. The laws of motion relative to the overall stock of ICT employed in production activities (k_t) and to the stock owned by households for consumption purposes (d_t) take the following forms:

$$\dot{k}_t = q_t i_t - \delta k_t, \tag{3}$$

$$\dot{d}_t = q_t c_{2t} - \delta d_t.^{3} \tag{4}$$

Our setup is consistent with Greenwood *et al.* (1997) who build a model characterized by the presence of both disembodied and embodied technical change (z_{it} and q_t) by integrating the original frameworks developed by

[3]The hypothesis of an identical geometric depreciation rate for digital assets (δ) used at home and on the workplace follows Jorgenson and Stiroh (2000).

Solow (1957) and (1960). Whereas q_t reflects technical advances incorporated in new asset types (*investment-specific* or *embodied* technical change), z_{it} measures the production efficiency gained over time that is not directly associated with any specific input (total factory productivity), and for this reason it is usually regarded as an index of *neutral* (or *disembodied*) technical progress. For the sake of simplicity, in what follows z_{1t} will be normalized to unity ($z_{1t} = 1$), implying that relative prices are driven only by TFP growth of ICT-producing industry:[4]

$$p_t = \frac{p_{2t}}{p_{1t}} = \frac{1}{z_{2t}} \;\Rightarrow\; g_p = -g_{z_2}, \tag{5}$$

where $g_p = \dot{p}_t/p_t$ and $g_{z_2} = \dot{z}_{2t}/z_{2t}$. The economy reaps the benefits of the embodied technical change when 'investing' in new technologies, while disembodied technical change flows across sectors through the movement of relative prices.

Household preferences. The representative infinitely-lived household has logarithmic preferences; the instantaneous utility depends on traditional consumption as well as on the flow of services provided (one-to-one) by the domestic stock of ICT:

$$u(c_{1t}, d_t) = \ln c_{1t} + \ln d_t.$$

The log-additive form excludes any complementarity between the two kinds of consumption.

Source of endogenous growth. Economic growth is assumed to be driven by the learning-by-doing process engendered by the usage of ICT. Since the advent of Information Age has speeded up the circulation of ideas and facilitated access to knowledge on both the production and the consumption side, the spillover is assumed to have a twofold source: capital assets employed by firms for productive purposes and durable goods owned by households for consumption. Following Boucekkine *et al.* (2003), the externality is assumed to affect the level of neutral and embodied efficiency in relative terms, with its total size being equivalent to the labour share ($\gamma + \lambda = \alpha$):

$$z_{2t} = z_2 f_z(d_t, k_t) = z_2(d_t^{\nu} k_t^{1-\nu})^{\gamma}, \tag{6}$$

$$q_t = q f_q(d_t, k_t) = q(d_t^{\mu} k_t^{1-\mu})^{\lambda}. \tag{7}$$

[4]This can be easily demonstrated by applying the dual production function approach.

Any parameter of (6) and (7) is a strictly positive real number. Furthermore, ν and μ must be less than one in order to restrict the externality to non-negative values.[5] On the one hand, γ and λ designate the vertical allocation of spillover (*disembodied vs. embodied*), while ν and μ define its horizontal assignment (*consumption vs. investment*). As a result, $\gamma\nu$ and $\lambda\mu$ measure the overall externality generated by ICT consumption on z_t and q_t, although, given the range of values admitted for the parameters, the spillover can be equivalently expressed in terms of firms' investment.

Determination of steady-state equilibrium. The household's problem of intertemporal optimization is to maximize its lifetime utility:

$$\int_0^\infty u(c_{1t}, d_t)\; e^{-\rho t} dt$$

with respect to c_{2t}, θ_t and l_t, subject to the constraints reported in equations (1)-(4); ρ (> 0) is the rate of time preferences. Solving the problem with the maximum principle, the two following transversality conditions must be imposed:

$$\lim_{t\to\infty} k_t\phi_{1t} = 0 \qquad \lim_{t\to\infty} d_t\phi_{2t} = 0,$$

where ϕ_{1t} and ϕ_{2t} are the costate variables associated with the ICT stock of firms and households and assuming positive values for the initial endowments, $k_0 > 0$ and $d_0 > 0$.[6]

Definition: *A steady-state equilibrium is an equilibrium where the variables* $\{c_{1t}, c_{2t}, y_{2t}, k_t, d_t, z_{2t}, q_t\}$ *grow at a constant but not necessarily identical rate, and the allocation shares of inputs* θ_t *and* l_t *are time-invariant.*

Along the steady-state equilibrium path, the above defined set of variables can be expressed in terms of the labour productivity growth of ICT-producing industry ($g_2 = \dot{y}_{2t}/y_{2t}$). To this end, one must initially express them as dependent on ICT capital deepening ($g_k = \dot{k}_t/k_t$) and then exploit the relation between g_2 and g_k.

First to be noted is that the steady-state growth rate of output per worker in ICT-using industry is simply $g_1 = \dot{c}_{1t}/c_{1t} = (1-\alpha)g_k$, because the allocation shares of factor inputs are constant over time (θ and l henceforth).

Second, differentiating the budget constrain of the innovative industry twice with respect to time, one can easily find the equivalence between

[5]In summary z_2 and $q \in\,]0,\infty[$, ν and $\mu \in\,]0,1[$, γ and $\lambda \in\,]0,\alpha[$.

[6]A detailed solution of the dynamic problem is provided in the Appendix.

$g_{c_2} = \dot{c}_{2t}/c_{2t}$ and $g_i = \dot{i}_t/i_t$ (and g_2 as well) stemming from the constancy of the consumption-income ratio c_{2t}/y_{2t} on the steady-state equilibrium. Exploiting this finding into (3) and (4), it turns out that the stocks of ICT used for productive and consumption purposes grow at the same rate ($g_k = g_d$, where $g_d = \dot{d}_t/d_t$);[7] this allows us to write the evolution of embodied and disembodied progress as $g_q = \dot{q}_t/q_t = \lambda g_k$ and $g_{z_2} = (\alpha - \lambda)g_k$.

Finally, the expression for g_q can be used to compute the labour productivity growth of ICT-producing industry, $g_2 = (1-\lambda)g_k$, that serves to reword any variable in terms of g_2:

$$g_1 = \frac{1-\alpha}{1-\lambda}g_2, \quad g_k = g_d = \frac{1}{1-\lambda}g_2, \quad g_q = \frac{\lambda}{1-\lambda}g_2, \quad g_{z_2} = \frac{\alpha-\lambda}{1-\lambda}g_2. \quad (8)$$

As a consequence, in order to determine the steady-state equilibrium of the economy it is sufficient to compute g_2:

$$g_2 = (1-\lambda)\big((1-\alpha)qz_2(d_0/k_0)^\epsilon - \delta - \rho\big), \qquad \epsilon = \gamma\nu + \lambda\mu. \quad (9)$$

This expression can be obtained with few algebra from the first order conditions of the Hamiltonian after replacement of the explicit formulas for z_{2t} and q_t (recall that private agents are not aware of the spillover effects of ICT). Equation (9) also exploits the fact that each industry employs factor inputs in the same proportion $(1-\theta = l)$, and that d_t/k_t can be rewritten in terms of the ratio between the initial endowments.

It should be emphasized that the growth rate of output per worker in the innovative sector depends on the total externality of ICT consumption, ϵ (or equivalently on that of firms' assets). g_2 is stable owing to the constancy of d_0/k_0 and positive under the following condition:

Assumption 1 $\quad (1-\alpha)qz_2\big(d_0/k_0\big)^\epsilon > \delta + \rho$.

The knife-edge condition on the overall amount of spillover $(\gamma + \lambda = \alpha)$ corresponds to the assumption of constant social returns on digital assets and induces the ICT-producing industry to behave as in the AK model. In this respect, Assumption 1 requires that the share of the social marginal productivity of ICT internalized by firms must be sufficient to compensate its physical deterioration and the value at which the future utility deriving from its utilization is discounted.

Proposition 1 *Under Assumption 1, there exists only one steady-state equilibrium.*

[7] To verify this, divide (3) and (4) respectively by k_t and d_t and then take the time log-derivatives.

Proof: See the Appendix. ■

At this point, to characterize the steady-state equilibrium fully, we need to find the optimal allocation of factor inputs between the two sectors. For this purpose, it is necessary to define the conditions under which the shares θ and l always fall within the interval $]0,1[$ and, at the same time, the size of ICT-producing industry does not exceed that of ICT-users.

Assumption 2 $1/2 < \frac{d_0}{k_0}(1-\alpha) < 1$.

Proposition 2 *Under Assumption 2, the allocation shares of inputs are always positive and less than unity along the steady-state equilibrium growth path, and their ratio is equivalent to that of nominal output* (recall $1-\theta = l$):

$$\begin{aligned} \frac{\theta}{1-\theta} &= \frac{1}{(1-\alpha)}\frac{k_0}{d_0} - 1 \\ &= p_t \frac{y_{2t}}{y_{1t}}. \end{aligned}$$

Proof: See the Appendix. ■

It is important to point out that the right-hand side of Assumption 2 ensures the existence of our economy because it guarantees that a non-null output is manufactured by each sector, $\theta/(1-\theta) > 0$. On the other side, the left term of the inequality preserves the consistency of the model with national accounts, given that ICT-producing industries account only for a minority share of GDP ($p_t y_{2t}/y_{1t} < 1$). As will be discussed in detail in the next section, the time-invariancy of the ratio between nominal outputs is a fundamental requisite for the stability of the aggregate growth.

Chaining rule of industry performance and aggregate growth. We next characterize the aggregate performance of our economy. The economy-wide growth rate of labour productivity (g) is calculated using the Divisia index formula which aggregates industries by means of the current output shares ($\omega_i = p_{it}y_{it}/\sum_{i=1}^{2} p_{it}y_{it}$, $i = 1, 2$). The continuous updating of weights avoids the substitution bias of fixed-year indexes (Laspeyres): the further back in time the base-year, the higher the aggregate growth rate because too high weights are attributed to those goods characterized by a marked decline in prices (Whelan, 2003). US National Income and Product Accounts moved to chain aggregation in 1996, in conjunction with a more extensive adoption of hedonic pricing for information equipment and electronic devices (Jorgenson, 2005).

A chaining rule is also utilized to estimate the aggregate growth of total factory productivity (g_z). We apply the method proposed by Domar (1961) and formally demonstrated by Hulten (1978) which considers g_z as the share-weighted growth of industry TFPs, employing as weights the current prices ratio between industry gross output and GDP. Since there are no intermediate inputs in our setup, gross output equals value added, and thus Domar's and Divisia's weights coincide (see Ho and Stiroh, 2001 and Oulton, 2006).[8]

As a result, the aggregate growth rate of labour and total factory productivity can be written as follows:

$$g = \omega_1 g_1 + \omega_2 g_2, \qquad g_z = \omega_1 g_{z_1} + \omega_2 g_{z_2}. \tag{10}$$

By employing (8) and recalling that g_{z_1} is zero, these rates can be finally reworded in terms of g_2:

$$g = g_2\big(1 - \frac{\gamma}{1-\lambda}\omega_1\big) = g_2 - g_{z_2}\omega_1, \tag{11}$$

$$g_z = (1-\omega_1)g_{z_2} = (1-\omega_1)\frac{\gamma}{1-\lambda}g_2. \tag{12}$$

Equations (11) and (12) highlight the key role played by ICT for economic growth and the mechanism underlying the process. The smaller the traditional production (ω_1), the higher the aggregate growth rate (g) as the ICT-using sector expands at the expense of the ICT-producing industry, which is the sole beneficiary of increasing returns to scale ($g_1 < g < g_2$). As shown by the second expression for g in equation (11), the cross-industry dynamic is driven by a transmission mechanism based on relative prices (*neoclassic pecuniary spillover*): a rise in TFP of ICT producers reduces g_p, encouraging firms to adopt cheaper and more efficient capital goods. Yet the larger the traditional sector, the less resources are available for ICT industry, and opportunities for further advances diminish.

Since the growth process is affected by the sectoral composition of the economy, a necessary condition for the existence of this kind of two-sector model is that the industry shares be constant; indeed, if the weight of the faster growing sector were rising, at a given time the traditional industry would disappear. This possibility is excluded by the time-invariancy of $p_t y_{2t}/y_{1t}$ (see Proposition 2), making the aggregate growth steady despite the discrepancy in the sector-specific rates.

[8]In presence of intermediate inputs, the sum of Domar weights exceeds unity because each sector contributes to aggregate TFP both directly in relation to the amount of final sales and, indirectly, through intermediate inputs sold to the other industries.

3.1 Productivity resurgence in the Information Age

Until the early 1990s the absence of correlation between investment and productivity fostered the belief that information technology was unable to promote growth. Several explanations have been advanced for this puzzle. In part, it was ascribed to measurement problems. First, the size of technical progress was underestimated because numerous studies failed to take account of the embodied component. Moreover, the base-year volume indexes overestimated the ICT capital stock, while, on the other hand, there was a systematic understatement of the real valued added of such intensively ICT-using industries as advanced services (communications, banking, R&D, etc). Furthermore, ICT required huge investments in complementary factors like organizational changes and skill upgrading; adjustment costs and learning periods seemed to confine the productivity benefits of technologically advanced capital to the long-run.[9] Yet, according to Boucekkine *et al.* (2003) the slowdown in the growth process was a cost inherent to embodied technical change; in fact, with the advent of information technology in the 1970s, new capital vintages were characterized by a more rapid rate of obsolescence, with the consequence that they were unable to spur productivity by their very nature.

Nevertheless, the United States sheered in the second half of the last decade, switching to a high growth regime. Before describing the comparative statics properties of the model and its ability to fit the US resurgence, some evidence is reported to prove the extent to which the embodied content of information technology has recently risen compared to the disembodied one. This exercise will also allow us to demonstrate how the technological breakthrough of the mid-1990s can be mapped into an increase in λ.

As in Cummins and Violante (2002) and Greenwood *et al.* (1997), it is possible to infer a measure of embodied and disembodied technical change by looking at inverse dynamics of the prices of semiconductors and ICT final goods (respectively p_{st} and p_{2t}) relatively to traditional output (p_{1t}), $q_t = p_{1t}/p_{st}$ and $z_{2t} = p_{1t}/p_{2t}$.[10]

[9] For discussion of these issues see respectively Oliner and Sichel (1994), McGuckin and Stiroh (2001), Brynjolfsson and Hitt (2000) and Bresnahan *et al.* (2002).

[10] The obvious shortcoming of the analysis is that it employs a steady-state framework to fit US economic growth over the short span of time after 1995. In line with the rationale of the model, the empirical exercise assumes that technical change only affects ICT productions (intermediate and final); hence the quality of traditional output is considered constant. By applying this variant of the dual approach we obtain estimates for TFP growth of ICT-producing industry, Case 3, not dissimilar from the values reported by O'Mahony and van Ark (2003, chap. III) in a growth accounting study grounded on the primal approach. They find that TFP grew at an annual rate of 12% in ICT-producing

The first section of Table 2 reports the annual growth rate of the deflators for industry value added over the periods 1979-95 and 1995-2002. The middle part displays the corresponding speed of the two forms of technical progress and their relative levels. Finally, the last column sets out the value of λ that can be subsumed from data using the formula of the ratio g_q/g_{z_2} which results from (8), applying a conventional value of 0.70 for α:

$$\frac{g_q}{g_{z2}} = \frac{\lambda}{\alpha - \lambda}. \tag{13}$$

This exercise is performed considering an increasingly broader definition of the ICT-producing (manufacturing) sector. Focussing on office machinery only (Case 1), given that this is the most strictly related to semiconductor advances, the year 1995 stands out as a turning point, because g_q starts to grow stably faster than g_{z_2} from then on. Moreover, the learning parameter of the incorporated efficiency (λ) is estimated to rise from 0.28 to 0.40, now prevailing against γ, which amounts to 0.30.

Several interesting points arise when one extends the compass of the ICT sector to include telecommunication equipment (Case 2), or all semiconductor-intensive activities (Case 3).[11] As expected, g_{z_2} is more moderate, since these sectors have experienced a lesser improvement in output quality compared to computers over time. As a result, the ratio between the two measures of technical change and the level of λ is higher. It is important to note that, unlike under Case 1, the parameter of embodied efficiency is equivalent to or exceeds the disembodied one already before 1995, but the subsequent increment is smaller. The reason for this finding may be that, for the extended groups of ICT sectors, the base of the learning process was sufficiently wide in the early 1990s; therefore, the technological shock of 1995 may have affected the knowledge content embodied in their output (and, hence, in the total economy's endowment of these assets) to a smaller extent with respect to computer industry.

Turning to the properties of the model, the following proposition formally states that, within our setup, a surge in the embodied component of technical progress relative to the disembodied one is compatible only with an upward jump of λ.

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industry and 0.4% in the rest of the economy between 1979 and 2001. Moreover, the labour share is relatively stable over time and between the two types of ICT sectors, being around 0.70.

[11] See OECD (2004, Annex B) for this classification. Case 3 does not consider semiconductors in order to preserve the consistency of the empirical exercise with the model; this simplification leaves the results unchanged, given the small share of their net export on GDP.

Table 2: **Estimation of technical change**, 1979-2002 (annual averages, %)

	g_{p_1}	g_{p_2}	g_{p_s}	g_q	g_{z_2}	g_q/g_{z_2}	λ	γ
Case 1. **Office machinery**								
1979-95	4.1	-26.2	-18.0	22.1	30.3	0.7	0.28	0.42
1995-2002	1.9	-35.8	-47.0	48.9	37.7	1.6	0.40	0.30
Case 2. **Office machinery & TLC equipment**								
1979-95	4.1	-15.5	-18.0	22.1	19.6	1.2	0.35	0.35
1995-2002	1.9	-23.9	-47.0	49.0	25.8	2.0	0.45	0.25
Case 3. **Broad ICT sector***								
1979-95	4.1	-4.9	-18.0	22.1	9.0	2.6	0.47	0.23
1995-2002	1.9	-10.0	-47.0	49.0	12.0	4.6	0.54	0.16

Source: Own calculations on GGDC 60 Industry Database (www.ggdc.net). For details see O'Mahony and van Ark (2003).
* *OECD (2004) classification*: Office Machinery (ISIC Rev.3 cat.30), Insulated wire (313), TLC equipment (322), Radio & TV receivers (323), Scientific instruments (331).

Proposition 3 *The information shock of the mid-1990s generates an increase in embodied technical change relative to the disembodied component implying:*

$$\Delta\lambda > 0 \quad (\Delta\gamma < 0).$$

Proof: This derives directly differentiating equation (13) with respect to λ. ■

As a consequence, our model aligns perfectly with Boucekkine *et al.* (2003) in considering the advances of information technology as a reassignment of the learning externality. The following proposition summarizes the economic impact of this technological breakthrough:

Proposition 4 *The increase in the embodiment of information technology* ($\Delta\lambda > 0$) *gives rise to an acceleration in*

i) *the quality growth of ICT goods* ($\Delta g_q > 0$),

ii) *the decline in relative prices* ($\Delta g_p < 0$),

iii) *the aggregate growth rate of labour and total factory productivity* ($\Delta g > 0$ and $\Delta g_z > 0$)

when the following conditions are fulfilled:[12]

1. if $\mu < \nu$ $\quad 1-\theta < \frac{1}{z_2 q} e^{-\frac{1}{\gamma(\nu-\mu)}}$;

2. if $\mu > \nu$ $\quad 1-\theta > \frac{1}{z_2 q} e^{\frac{1}{\gamma(\mu-\nu)}}$.

Proof: See the Appendix. ■

Proposition 4 defines a critical threshold for the proportion of factors' utilization and, accordingly, for the relative size of sectors (see Proposition 2).[13] It can be interpreted as follows. When the externality of consumption is greater on the disembodied component of production efficiency, we know that the majority of knowledge spillover associated with firms' endowments of ICT is of the embodied form ($\mu < \nu$, Proposition 4.1).[14] Therefore, there is mutual reinforcement between the two growth effects of firms' assets, i.e. the direct impact concerning k_t as a production factor and the indirect one as a source of spillover. This aspect emphasizes the role of firms' accumulation of ICT in development, as well as the production of these kinds of goods: the larger the innovative sector (i.e. $1-\theta$ must not be excessively high), the more technical advances accrue to the final users of digital technologies (consumers and firms). This enables the economy to obtain greater benefits from enhancement of the embodied nature of information technology. Clearly, the reverse holds when $\mu > \nu$ (Proposition 4.2).

The mechanism at the basis of the American resurgence can thus be summarized as follows (see also Section 2). The take off originated in the semiconductors market, where technological advances delivered large efficiency gains and price reductions ($\Delta\lambda > 0$) directly favoring the final productions of ICT. Firms and households responded to the improved quality and lower prices of computers and communication equipment by increasingly adopting these kinds of goods ($\Delta g_q > 0$ and $\Delta g_p < 0$). Faster ICT capital deepening triggered an acceleration in labour productivity ($\Delta g > 0$) whilst, on the other hand, aggregate TFP soared because of the efficiency improvement of ICT producers ($\Delta g_z > 0$). The economy also benefited from a positive externality deriving from the use of ICT in homes and in workplaces. It is only since the mid-1990s that information technology has reached the critical threshold to foster the growth process.

[12]These conditions are *necessary* for an acceleration in g_z ($\partial g_z/\partial\lambda > 0$) and *sufficient* for a jump in g ($\partial g/\partial\lambda > 0$); obviously, the dynamics of the aggregate rates are driven by their industry counterparts (g_1, g_2 and g_{z_2}).

[13]Proposition 4 is binding only if the levels reported on the right-hand side of the two inequalities fall within the range of values admitted for $1-\theta$ (see Assumption 2).

[14]$\mu < \nu \Leftrightarrow 1-\mu > 1-\nu$.

4 Discussion

Two-sector economy and the role of technical change. It is evident from the previous sections that the structure of the model is founded on three pillars. First, it rests on the multi-sector setup proposed by Whelan (2003) because of its ability to represent the main macroeconomic trends exhibited by the US since the 1960s.[15] Second, it shares with Boucekkine *et al.* (2003) the idea that advances in information technology have induced a reassignment of the learning process. Third, it explicitly recognizes ICT consumption as a source of spillover. It is important to bear in mind that the former model assumes exogenous growth rates for TFP and the absence of investment-specific technological change ($q_{it} = 1$), while the latter corresponds to the one-sector version of the model presented here if one excludes the home adoption of information technology ($c_{2t} = 0$) and the related externality ($\nu = \mu = 0$).

The economy described in this paper behaves similarly to the two-sector version of Rebelo (1991), with the difference that our firms internalize only some of the marginal returns of (digital) capital, and households are allowed to consume durable goods. Felbermayr and Licandro (2005) have shown that the two-sector AK model proves to be the simplest endogenous growth model compatible with the development path of the US in the post World War II period. Moreover, if one introduces an industry-specific process of learning, it is equivalent to the social planner's version of Boucekkine *et al.* (2003). Hence, the two-sector version of Rebelo (1991) can be considered a model of technical change, even though it does not offer clear indications on the growth effects of the embodiment of technology.

It is therefore from this point of view that our model makes a step forward in this strand of the literature. Indeed, besides providing a stylized description of the Information Age, it stresses the growth enhancing role of high-tech consumption and thus excludes any isomorphism with Boucekkine *et al.* (2003); no less importantly, it also identifies the conditions under which embodied technological change is able to spur economic growth.

Two-sector economy and unbalanced development. As displayed in Section 3, the framework developed by Whelan (2003) is characterized by an identical factor proportion across industries. This hypothesis is consistent with national accounts indicating a similar long-run labour share between ICT-producers and -users, but substantially diverging total factory produc-

[15] A downward trend in relative prices of equipment, stationary shares of consumption and investment on nominal output, a faster rise of real investment with respect to real output.

tivity. From a theoretical perspective, it entails that the key determinant of structural change in modern economies is the different growth rate of TFP across sectors (Ngai and Pissarides, 2006). This differential ultimately explains why economic growth is biased towards ICT goods in our setup and, accordingly, why the equilibrium solution is defined as a *steady-state* rather than a *balanced* growth path.

The issue of a non-balanced development has been analyzed in detail by Acemoglu and Guerrieri (2006), who show that (un)balanced economic growth is not compatible with (un)balanced technological change within a multi-sector framework in the presence of capital deepening and different factor proportions. This highlights that our model's prediction of a joint unbalanced economic and technological growth derives from the hypothesis of homogeneous output elasticity to factor inputs across industries.

A further consequence of this assumption is that the two sectors employ inputs exactly in proportion to their relative size (see Proposition 2). This should not induce the (erroneous) conclusion that ICT-users invest more in information technology than producers do, while it is well-known that the latter present higher adoption rates. Indeed, the degree of a sector's technological intensity is usually defined on the basis of the share of ICT on total capital services, obtained by attributing to each kind of asset a weight reflecting its rental price (Stiroh, 2002b).

ICT Consumption as a source of endogenous growth. The core idea of this paper is that both investment and consumption fuel Arrowian learning-by-doing. This assumption is not new in the literature;[16] however, complementarity between productive capital and consumer durables seems to be a distinctive feature of information technology. In fact, new technologies such as communication devices tend to generate network (technical) externalities, heightening the interactivity between firms and households. Moreover, ICT enables the dissemination of knowledge and hence favors the occurrence of spillovers. In this regard, information technology differs considerably from more traditional forms of consumption; it is used to satisfy higher-order needs (education, knowledge, entertainment, etc), in contrast to traditional goods,

[16]See, for instance, Dasgupta and Marjit (2002). Steger (2002) instead analyzes the growth impact of consumption whenever it influences the marginal productivity of workers or the accumulation of human capital. It should be noted that in our paper the spillover of ICT is rival both vertically and horizontally, given that its overall magnitude is assumed to be exogenous (α). By contrast, Bresnahan and Trajtenberg (1995) model the externality of GPTs as being endogenously fed, on the one hand, by the technological complementarity between producers and users and, on the other hand, by the commercial complementarity existing among the users of new technologies.

which are instead targeted on basic necessities (nutrition, clothing, etc.). As formalized in the model, digital technologies behave similarly to capital goods both by gradually releasing their utility content to consumers and by acting as a source of learning-by-doing.

The double-sided growth effect of ICT has been emphasized by Quah (2003) and Petit and Soete (2001) who stress how strongly it affects both business activities (supply-side) and the employability of home users (demand-side). This second 'face' of information technology has prompted numerous policies aimed at closing the *digital divide*, i.e. the gap in both home adoption of ICT and access to the Internet that exists *across* and *within* countries.[17] In societies increasingly based on knowledge-intensive activities, the distribution of knowledge matters, because it conditions how individuals accumulate human capital, find jobs and exploit opportunities to grow. In the long-run, therefore, the possibility of increasing the economy's efficiency and wealth relates to 'investment' in digital technologies for both productive and consumption purposes.

Comparative statics with respect to ν and μ. In light of these considerations, it is interesting to assess the macroeconomic effects of a change in the learning process associated with ICT consumption. Given the model's assumptions, an increase in ν or μ determines a simultaneous (identical) fall in the corresponding *horizontal* spillover of productive capital (see (6) and (7)). This means that, in terms of both labour and total factory productivity, the reaction of the economy will depend on the relative size of the ICT stock owned by firms and households. The widening of the consumption externality on the disembodied efficiency, ν (or, equivalently, on the embodied one, μ) accelerates the growth process only when the amount of ICT goods used at home, d_t, is superior to the firms' endowment, k_t. By contrast, when productive capital exceeds the stock of consumer durables, there is a slowdown in aggregate performance, g and g_z.[18] This outcome is formally stated by the following proposition:

Proposition 5 *The growth impact of a change in the horizontal assign-*

[17]See OECD (2002, chap. 6 and 8). Quah (2006) analytically assesses the welfare gains arising from closing the digital divide, the speed at which following countries reduce their distance from the digital technological frontier, as well as the within-society distribution of information technology.

[18]Recall that, along the steady-state equilibrium growth path, the differential between d_t and k_t eventually reflects that between the initial endowments. Note that, for conventional values of the labour share ($\alpha > 1/2$), Assumption 2 implies that d_0/k_0 is larger than one; in this case, an increment in ν or μ accelerates the growth process.

ment of the learning externality, ν or μ, varies with the relative size of the ICT stock owned by firms and households.

Proof: From (11) it is evident that both $\partial g/\partial \nu$ and $\partial g_z/\partial \nu$ depend simply on $\partial g_2/\partial \nu$, with $\partial g_2/\partial \nu = (1-\lambda)A\gamma \ln(d_0/k_0)$.[19] The sign of this expression changes in relation to the value of d_0/k_0: if this ratio is larger than one, g_2 accelerates; if inferior, it decelerates. The demonstration is analogous for the analysis of comparative statics with respect to μ. ■

A growth model for the Information Age. One important feature of the paper is that it provides an accurate description of the mechanism underlying the recent US growth path. It considers the productivity gains linked to both the production and the use of ICT, as well as the indirect external effects (spillovers) deriving from the deployment of these new technologies.

The dichotomy between producers and users has been central to the IT literature since its infancy (Baily and Gordon, 1988). Information technology was not considered a primary source of growth as long as its impact remained confined to few durable sectors (Gordon, 2000). Recently, however, numerous works have described the pervasiveness of digital technologies, and the US acceleration is almost entirely ascribed to the sectors that manufacture and intensively use these kinds of assets (Stiroh, 2002b).

The prominence of the direct effects exerted by information technology on the US resurgence was first assessed by Oliner and Sichel (2000) and Jorgenson and Stiroh (2000). The largest contribution to labour productivity step-up is found to derive from the rise in ICT stock per hour worked (see above Table 1). On the other hand, however, much emphasis has also been placed on the innovative efforts of ICT producers, whose technological advances accrue to downstream sectors in the form of pecuniary externalities.

Aggregate evidence on the technical (non-pecuniary) spillovers of ICT is still rather scarce. This partly depends on the well-known methodological difficulties involved in detecting such effects; these issues are discussed by Stiroh (2002a) who, in fact, does not find any statistically significant association between ICT capital deepening and TFP growth for the US manufacturing industries. Nevertheless, new findings compatible with the presence of such externalities have been recently reported by O'Mahony and Vecchi (2005) in a work focussed on the long-run effects of ICT for all the US market sectors. Mun and Nadiri (2002), instead, investigate whether there are spillovers associated with inter-industry transactions. They find that the ICT stock of suppliers and customers positively affects own production efficiency;

[19] $A = (1-\alpha)qz_2(d_0/k_0)^{\epsilon}$.

on the whole, IT externalities account for a considerable part of aggregate TFP growth over the period 1984-2000.[20]

5 Concluding Remarks

Information technology is widely acknowledged as being the key factor in the US productivity revival. By the mid-1990s ICT had revolutionized both firms' activity and household lifetime, delivering higher levels of efficiency and wealth. This paper has proposed a model where the endogenous engine of growth is the learning-by-doing process associated with the use of ICT at home and in the workplace. The advent of the Information Age has been described by means of a two-sector framework (à la Whelan) that, by distinguishing between ICT producers and users, is able to fit the recent growth performance of the United States. Around 1995, the extraordinary surge in semiconductor efficiency enhanced the incorporated nature of progress, making new types of ICT assets enormously more productive. The consequent fall in relative prices enabled the global diffusion of new technologies, which have thus reached the critical threshold to foster the growth process. As formalized in our model, information technology has boosted US labour productivity through a threefold effect: more rapid capital deepening, a marked increase in the efficiency of ICT producers, and the spillover determined by its deployment by firms and households.

[20]Outside the US, the outcomes on the growth impact of ICT are weaker, particularly in Europe. Timmer and van Ark (2005) show that the entire EU-US growth gap in labour productivity is attributable to the differential rise in ICT capital deepening and TFP levels of ICT-producing industries. Whereas the latter effect clearly reflects the inferior technological specialization of the EU, the former is influenced by various burdensome regulatory practices that reduce firms' incentives to exploit information technology (Bassanini and Scarpetta, 2002 and Gust and Marquez, 2004). In Europe, there is also a poor evidence on ICT spillovers, even in the case of Finland, the only one real example of a new economy in the EU, where technical external benefits are not found to accrue from Nokia (and its industrial cluster) to the rest of the economy (Daveri and Silva, 2004).

Appendix

The hamiltonian function of the dynamic problem of the representative household is:

$$H(.) = u(c_{1t}, d_t)\ e^{-\rho t} + \phi_{1t}\{q_t y_{2t} - q_t c_{2t} - \delta k_t\} + \phi_{2t}\{q_t c_{2t} - \delta d_t\}.$$

Considering the explicit expressions for c_{1t} and y_{2t} from (1) and (2) of the main text, the first-order maximum conditions with respect to the control (θ_t, c_{2t} and l_t) and state variables (k_t and d_t) are the following:

$$\frac{\partial H(.)}{\partial \theta_t} = 0 \quad \Rightarrow \quad \frac{1}{1-\theta_t} e^{-\rho t} = \phi_{1t} q_t \frac{y_{2t}}{\theta_t},$$

$$\frac{\partial H(.)}{\partial c_{2t}} = 0 \quad \Rightarrow \quad \phi_{1t} = \phi_{2t},$$

$$\frac{\partial H(.)}{\partial l_t} = 0 \quad \Rightarrow \quad \frac{1}{l_t} e^{-\rho t} = \phi_{1t} q_t \frac{y_{2t}}{1-l_t},$$

$$\frac{\partial H(.)}{\partial k_t} = -\dot{\phi}_{1t} \quad \Rightarrow \quad -\dot{\phi}_{1t} = (1-\alpha)\frac{1}{k_t} e^{-\rho t} + \phi_{1t}\big((1-\alpha) q_t \frac{y_{2t}}{k_t} - \delta\big),$$

$$\frac{\partial H(.)}{\partial d_t} = -\dot{\phi}_{2t} \quad \Rightarrow \quad -\dot{\phi}_{2t} = \frac{1}{d_t} e^{-\rho t} - \phi_{2t}\delta.$$

We must also impose that the initial values of the stock variables are positive ($k_0 > 0$, $d_0 > 0$) and that the two transversality conditions are satisfied:

$$\lim_{t\to+\infty} k_t \phi_{1t} = 0, \quad \lim_{t\to+\infty} d_t \phi_{2t} = 0.$$

In the main text (eq. 8) we have shown that, along the steady-state growth path, the entire set of time-varying variables can be expressed in terms of labour productivity growth of the ICT-producing sector (g_2).
To compute g_2, one must substitute $g_q = g_2\ \lambda/(1-\lambda)$ into the time log-derivative of the first FOC ($\partial H(.)/\partial \theta_t$), recalling that the allocation shares of inputs are constant on the steady-state equilibrium. Rearranging, this yields:

$$g_2 = (1-\lambda)\big(-\frac{\dot{\phi}_{1t}}{\phi_{1t}} - \rho\big).$$

$-\dot{\phi}_{1t}/\phi_{1t}$ can be straightforwardly calculated by replacing the expression for ϕ_{1t} resulting from $\partial H(.)/\partial \theta_t$ in $\partial H(.)/\partial k_t$, after dividing the latter equation by ϕ_{1t} itself:

$$-\frac{\dot{\phi}_{1t}}{\phi_{1t}} = (1-\alpha) q_t z_{2t} k_t^{-\alpha} - \delta.$$

The previous finding exploits the condition $\theta = 1-l$ stemming from the ratio between $\partial H(.)/\partial\theta_t$ and $\partial H(.)/\partial l_t$; it means that each sector employs labour and capital inputs in the same proportions. Introducing $-\dot{\phi}_{1t}/\phi_{1t}$ into g_2 and taking into consideration the expressions for q_t and z_{2t} (see eq. (6) and (7)) we have:

$$g_2 = (1-\lambda)\big((1-\alpha)qz_2(d_0/k_0)^{\epsilon} - \delta - \rho\big) \qquad \epsilon = \gamma\nu + \lambda\mu,$$

where d_t/k_t has been reworded in terms of the ratio of their initial endowments, provided that $g_d = g_k$. g_2 is always positive under the conditions imposed by Assumption 1.

By means of easy algebra, it is also possible to verify that the transversality conditions are satisfied. Replacing ϕ_{1t} from the first FOC into $\lim_{t\to+\infty} k_t\phi_{1t}$, expressing the variables in terms of g_k and simplifying, one can see that the limit goes to zero when $\rho > 0$; this condition is true by assumption. The same holds for the second transversality condition.

Proof of Proposition 1

In our dynamic system, a closed form for ICT consumption (c_{2t}) can be obtained from each law of motion (eq. (3) and (4)). Since d_t and k_t grow at the same rate in the steady-state equilibrium, from the dynamic constraints respectively it follows that $g_k + \delta = \frac{q_t}{k_t}(y_{2t} - c_{2t})$ and $g_k + \delta = \frac{q_t}{d_t}c_{2t}$, whose ratio yields:

$$\frac{c_{2t}}{y_{2t}} = \frac{d_0}{d_0 + k_0}.$$

This expression rests on the formulation of the steady-state ratio between the state variables as d_0/k_0. It is always constant, positive and less than unity because of the assumptions on the initial endowments; therefore, for any level of y_{2t}, there exists only one steady-state value for ICT consumption. ■

Proof of Proposition 2

As a first step, calculate $p_t y_{2t}/y_{1t}$ from eq. (5), (2) and (1), exploiting the equilibrium condition $l_t = 1 - \theta_t$:

$$p_t\frac{y_{2t}}{y_{1t}} = \frac{\theta_t}{1-\theta_t}.$$

The steady-state ratio between θ_t and $1-\theta_t$ can be obtained from the first FOC. To this end, one needs to find ϕ_{1t}, which can be easily derived by equalizing $\dot{\phi}_{1t}/\phi_{1t}$ and $\dot{\phi}_{2t}/\phi_{2t}$ from the last two FOCs, given that $\phi_{1t} = \phi_{2t}$. Substituting the expression for ϕ_{1t} into $\partial H(.)/\partial\theta_t$ (and simplifying) yields the ratio $\theta_t/(1-\theta_t)$ whose value is given in Proposition 2, from which one can extrapolate the steady-state value of each share, $1-\theta_t = \frac{d_0}{k_0}(1-\alpha)$. ■

Proof of Proposition 4

Consider the simplified version of the aggregate growth rate of labour and total factory productivity resulting from eq. (11) and (12), where now $\chi = \gamma/(1-\lambda) = (\alpha-\lambda)/(1-\lambda)$:

$$g = g_2(1-\chi\omega_1), \qquad g_z = g_2(1-\omega_1)\chi.$$

The reallocation of the learning process due to the information shock ($\Delta\lambda > 0$) generates an acceleration in both indexes when the following conditions are verified:

$$\frac{\partial g}{\partial\lambda} > 0 \quad \Leftrightarrow \quad \frac{\partial g_2}{\partial\lambda} > g_2\frac{\partial\chi}{\partial\lambda}\omega_1\frac{1}{(1-\chi\omega_1)},$$

$$\frac{\partial g_z}{\partial\lambda} > 0 \quad \Leftrightarrow \quad \frac{\partial g_2}{\partial\lambda} > -g_2\frac{\partial\chi}{\partial\lambda}\frac{1}{\chi}.$$

Since $\partial\chi/\partial\lambda$ is less than zero, the right-side term is negative in the first inequality and positive in the second one; as a consequence, $\partial g/\partial\lambda > 0$ is implied by $\partial g_z/\partial\lambda > 0$.

To determine the conditions ensuring $\partial g_z/\partial\lambda > 0$, we need to explicit χ and $\partial\chi/\partial\lambda$ and consider that:

$$\partial g_2/\partial\lambda = -(A-\delta-\rho) + (1-\lambda)A\kappa,$$

where $A = (1-\alpha)qz_2(d_0/k_0)^\epsilon$ and $\kappa = (\mu-\nu)\ln((1-\alpha)qz_2(d_0/k_0))$.

Using the previous equation, $\partial g_z/\partial\lambda > 0$ can be finally rewritten as follows:

$$A\kappa > (A-\delta-\rho)\frac{1}{\gamma}.$$

There is certainty that this inequality is verified when $\kappa > 1/\gamma$, that is under the conditions reported in Proposition 4, which have been obtained by exploiting the steady-state value of $1-\theta$ (see above the proof of Proposition 2). ■

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