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

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Abstract

By the mid-1990s, the extraordinary advances in semiconductors enhanced the embodied nature of information technology, fuelling the efficiency growth in computers and communication equipment industries. The consequent fall in prices enabled the rapid diffusion of these new technologies, which have thus reached the critic 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. Relying upon a two-sector framework (à la Whelan) that distinguishes between ICT-producers and -users, our model provides a sound representation of the stylized facts of the Information Age.

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

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1 Introduction

In the mid-1990s the United States entered the often-called Information Age. After a long period of sluggishness, labour productivity switched to a high growth regime, in a large part due to the efficiency improvement in ICT productions and the intensive deployment of these types of asset.

Around 1994-95, the changeover from a three- to a two-year product cycle of microelectronic components determined a stellar fall in prices (around 90% per year). As a consequence, a large array of goods incorporating semiconductors as intermediates inputs (primarily computers) have become more efficient and cheaper, spreading rapidly throughout the economy (Jorgenson (2001)). ICT capital deepening and TFP growth in ICT-producing industries are found to entirely account for the recent acceleration in GDP per hour worked[1], dispelling definitively any residual doubt about the growth impact of information technology (see for instance Gordon (2003)). Meanwhile, as documented by Jorgenson and Stiroh (2000), consumers' purchases of computers parallelled the uptake of firms[2]. To the extent to which ICT

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[1] See Oliner and Sichel (2000), Jorgenson (2001) and Jorgenson *et al.* (2003). A comparison between the US and the EU-15 is provided by Timmer and van Ark (2005).

[2] Venturini (2006) shows how the growth contribution of IT consumption is larger than that of investment in communication equipment and software in the US as well as in most EU countries.

has transformed both household life and the way to conduct business practices, it can be regarded as a general purpose technology (Jovanovich and Rousseau (2005)).

According to Quah (2003) and Petit and Soete (2001), the effect of information technology on economic growth is twofold: as embodying new knowledge it improves both the productive efficiency of firms (supply-side) and the employability of home users (demand-side); thereby, accounting for the home usage of new technologies becomes crucial to fully understand their growth potential. Being a durable good, ICT differs from traditional consumption since releases gradually the utility content, acting similarly to capital goods in production. Furthermore, ICT usage aims at satisfying upper needs of consumers (education, knowledge, entertainment, etc), in contrast to traditional goods that are targeted to basic necessities (food, clothing, etc.). Finally, such types of new technologies as communication devices are likely to generate network externalities so that the economy takes advantage from the increasing number of users. It is therefore evident that a society may reach higher levels of welfare in the long-run by allocating more resources to ICT for consumption purposes along with for productive ones.

This paper proposes a model where the growth enhancing role of ICT derives from a learning-by-doing process involving both firms and households. In line with the empirical literature on information technology, the work considers a multi-sector economy distinguishing between ICT producers and users. By the mid-1990s, the sizeable improvement in semiconductors' efficiency has boosted the embodied nature of information technology, giving rise to a productivity upsurge in ICT industry; the consequent fall in relative prices has favored the rapid adoption of ICT by firms and households. Finally, the sharp increase in labour and total factory productivity can be fully traced to the faster ICT capital deepening, the efficiency improvement of ICT producers and the spillover effects associated to the usage of new technologies.

The work is organized as follows. Section 2 summarizes the debate prompted by Jorgenson (1966) and Solow (1960) on the nature of technical progress (embodiment controversy). Section 3 lays out the model and shows the conditions under which it is able to fit the US growth pattern of the last decade. Finally, Section 4 concludes.

2 Technical Change and Growth

The embodiment controversy gravitates around the way to model the growth impact of technical change. It dates back to the 1960s and, recently, has been revived by the number of neoclassic studies investigating the US resurgence and the influential paper by Greenwood, Hercowitz and Krusell (1997) (hereinafter GHK).

The neoclassic stream of literature follows Jorgenson (1966) in considering technology as disembodied (or neutral), as originally postulated by Solow (1957). On the other hand, dynamic general equilibrium models regard it as investment-specific, i.e. embodied in new capital vintages (Solow (1960)).

Disembodied technical change represents the production efficiency gained over time ($y_t = z_t f(l_t, k_t)$) and is usually measured as the residual growth of output over the share-weighted change of factor inputs. It reflects a quantitative vision of technology (or process-oriented) that translates into outwards shifts of production function. In this connection, z_t can be considered as a raw index of social welfare, even though it does not allow for the quality improvement of final goods (loving for variety).

Nevertheless, when the true nature of progress is not neutral, but biased towards a more intensive use of any input ($y_t = f(\alpha l_t, \beta k_t)$), the Solow's residual consists in a weighted average of factor-specific technical changes ($g_z = \alpha g_l + \beta g_k$). Therefore, it might change in response to a variation in income shares rather than for scientific advances (see Hulten (2000)). More generally, z_t collects any mis-specification of the model (omitted variables, measurement errors, imperfectly competitive markets, increasing returns and externalities), ending to be only a poor proxy of technological change. Most importantly, the neutral view of progress does not take into an explicit consideration the mechanism through which the economy reaps the benefits of progress; it occurs by adopting new capital goods which incorporate innovations (Solow (1960)). This also implies that investment should be measured in quality adjusted units ($q_t i_t = i_t^*$), as different capital vintages are not economically comparable; as a consequence, the dynamics of the economy is determined by $y_t = f(l_t, k_t) = c_t + i_t$ and $\dot{k_t} = i_t^* - \delta k_t$[3].

According to Jorgenson (1966) the indexes of neutral and embodied technical change coincide numerically, since z_t picks up any unmeasured improvement in factor inputs' quality (q_t). Moreover, q_t should also be considered neutral since it does not modify the relative contribution of inputs to the production of capital assets. A valid alternative would be adopting a multisector framework that admits a faster TFP growth for investment goods producers.

Hercowitz (1998) stresses however that, at the economy-wide level, the

[3]The index of investment quality (q_t) puts various vintages onto a common ground based on the effective contribution to output; at the same time, it also determines the obsolescence rate of capital. δ instead represents wear and tear, i.e. the loss of the productive capacity of each vintage due to utilization.

perfect substitution between quality-adjusted final goods advanced by Jorgenson (1966) would produce counter-factual results ($y_t = f(l_t, k_t) = c_t + i_t^*$). In fact, perfect competition forces the prices of investment (in effective units) and consumption goods to be identical in equilibrium; provided that q_t is inversely related to the relative prices at the aggregate level ($p_t = 1/q_t$), this means that also q_t converges to the unity within the jorgensonian set-up, ruling out any role for technical change[4].

Along with investment, Hulten (1992) affirms that qualitative adjustment should involve capital as well. So doing, the Solow's residual coincides with the true index of technical change when the share-weighted growth rate of quality of both kinds of goods is equal. As such a condition held for a long time in the US, he concluded that the technological performance could be correctly inferred by looking at the residual.

It is with the appearance of the productivity slowdown that criticism against the disembodied conception of technology became fiercer. Despite the massive uptake of CAD-CAM systems, computers, etc., the sluggishness of GDP per employed revealed that new technologies did not have any significant productive impact (Greenwood and Jovanovic (1998)). In part, the puzzle could be ascribed to the fact that TFP accounted only for a fraction of the growth impact of technical change and, probably, some productivity gains remained veiled. In this respect, Greenwood *et al.* (1997) develop an aggregate framework featured by the cohabitation of neutral and investment-specific technical change (z_t and q_t). As the latter affects only equipment (k_{et}) -but not structures (k_{st})-, the economy can be described as follows:

$$y_t = z_t f(l_t, k_{st}, k_{et}) = c_t + i_{st} + i_{et},$$

$$\dot{k}_{et} = q_t i_{et} - \delta_e k_{et}, \quad \dot{k}_{st} = i_{st} - \delta_s k_{st}.$$

Calibrating the model, GHK show that the long-run growth in the US GDP per capita is explained for a 40% by disembodied technical change and the remaining 60% by the embodied component[5].

Boucekkine *et al.* (2003) utilize a simplified version of the previous framework to show that the productivity slowdown is a by-product of the embodiment process. The advent of ICT in the early 1970s induced a reassignment of learning-by-doing process of capital from the neutral to the incorporated

[4]Ho and Stiroh (2001) and Oulton (2005) claim that the growth accounting framework criticized by Hercowitz (1998) cannot be attributed to Jorgenson (1966).

[5]Hercowitz (1998) disentangles the contribution of investment-specific technical change into two components. The former stems from quality improvement of investment, given the existing level of capital (38%); the latter is the acceleration in capital accumulation induced by quality improvement of investment goods (22%).

component of technology. It determined a decline in relative prices that enabled the uptake of new technologies by business. Yet, the obsolescence of new capital goods was so high to fully offset the expansive role of spillover and, as a consequence, labour productivity slowed down.

Recently, Whelan (2003) has claimed the second postwar growth of the US cannot be represented by the one-sector version of Solow-Ramsey model. In alternative, he proposes a two-sector framework characterized by different growth rates between durable and non-durable goods and, meanwhile, time-invariant output shares. Also, Ho and Stiroh (2001) underline that a one-sector model is not able to explain the declining trend in relative prices as forcing the price of final goods measured in physical units to be identical. According to these authors, this is the reason why Greenwood *et al.* (1997) introduce a quality index of investment and deal with effective units.

Oulton (2005) demonstrates that the GHK's framework is a particular case of the two-sector economy à la Whelan since it relies upon on an implicit investment sector; in addition, GHK utilize a method to deflate aggregate output at odds with national accounts, as based on the price index of non-durable consumption.

In line with this body of studies, Felbermayer and Licandro (2005) show how the two-sector version of Rebelo (1991)'s model is consistent with the formalization of the US economy put forward by Whelan (2003) when is the investment goods industry to be characterized by an AK technology.

3 The model

Jorgenson (2001) and Oliner and Sichel (2000) have shown that a large fraction of the ICT contribution to the US economic growth can be traced to the fundamental efficiency gains of semiconductors industry. Microprocessors are embodied into an increasing array of products -primarily computers and communication equipment- so to be regarded as the inner general purpose technology at the basis the Information Age. Such technologically advanced intermediate inputs are comparable to the most important inventions of the past like steam engine and electricity, because of a pervasive use in a wide range of sectors and a technological dynamism (Bresnahan and Trajtenberg (1995), p. 84).

In this paper we develop a two-final sectors model that takes into account the rise in the incorporated nature of information technology resulting from the shock of the mid-1990s. The original framework proposed by Whelan (2003) is not able to describe accurately the forces behind the most recent growth pattern of the US; in fact, being based on final productions, it leaves no room for intermediate inputs. Although, following the stream of literature on the embodiment, this lack can be easily filled by introducing an (implicit) index of productivity for intermediate electronic productions. We assume that the engine of growth is the learning process stemming from the usage of ICT goods at home and on the workplace; therefore, our model can be considered a two-sector version of the Boucekkine *et al.* (2003)'s economy, whose properties are similar to those described by Felbermayer and Licandro (2005).

In our information-based economy the traditional sector produces only consumption goods (y_{1t}); in so doing, it utilizes ICT assets manufactured by the innovative industry (y_{2t}). The output of the durable sector can be used either as capital goods in firms' activity or consumed by households (i_t and c_{2t}); in both cases, ICT goods show a qualitative improvement relatively to the old vintages, since incorporate more efficient technologically advanced intermediate inputs (q_t)[6]. The dichotomy between producers and users has always been central in IT literature. Information technology was not considered as a primary source of growth until its positive effects remained confined to few durable sectors (Gordon (2000)). Nowadays there is a wide evidence on the pervasiveness of such technologies; in fact, Stiroh (2002b) find that the acceleration in the US labour productivity can be totally attributed to those sectors producing and intensively using ICT.

In line with Whelan (2003) it is hypothesized an identical factor proportion between sectors. As Ngai and Pissarides (2006) point out, such an assumption leads to identify the key determinant of structural change in modern economies with the different TFP growth rates across sectors. This is consistent with national accounts that indicate a similar long-run labour share between ICT producers and users, but substantially diverging total factory productivity[7]. The labor supply is exogenous and there is no demographic dynamics; as a consequence, any variable is expressed in effective units and y_{it} measures industry labour productivity:

$$y_{1t} = z_{1t} k_{1t}^{1-\alpha} l_t^{\alpha}, \quad y_{2t} = z_{2t} k_{2t}^{1-\alpha} (1 - l_t)^{\alpha}, \tag{1}$$

$$\dot{k}_t = q_t i_t - \delta k_t, \qquad \dot{d}_t = q_t c_{2t} - \delta d_t, \tag{2}$$

[6]The architecture of our economy reflects the main characteristics of the baseline multi-sectoral framework developed by Ngai and Pissarides (2006). In that paper, however, the output of the pioneering industry (manufacturing) is consumed instantaneously by households, as not treated as a durable good; therefore, it does not differ from traditional consumption.

[7]Labour share amounted 0.70 in the US between 1980-2001, while TFP averagely grew by a nearly 12% per year in ICT producing industries against about 0.4% of the rest of the economy. See O'Mahony and van Ark (2003). ICT producing sectors correspond to categories 30-33 of ISIC Rev. 1 classification.

where $k_t = k_{1t} + k_{2t}$[8]. For simplicity we normalize z_{1t} to the unity; as a result, by applying the dual approach of production function to our competitive economy, one can see how relative prices are driven by TFP growth of ICT industry ($p_t = 1/z_{2t} \;\Rightarrow\; g_p = -g_{z2}$).

The representative infinitely-lived household has logarithmic preferences, depending on traditional consumption and the flow of services provided (one-to-one) by the domestic stock of ICT ($u(c_{1t}, d_t) = \ln c_{1t} + \ln d_t$). Households own firms and choose how to allocate capital between the two sectors by means of the share θ_t ($k_{2t} = \theta_t k_t$).

Learning-by-doing is identified as the endogenous engine of growth, affecting the level of neutral and embodied efficiency in relative terms ($\gamma + \lambda = \alpha$), as modelled by Boucekkine *et al.* (2003). Here, however, there are two potential sources for ICT spillover: capital assets employed by firms for productive aims and durable goods owned by households for consumption:

$$z_{2t} = z_2 f_z(d_t, k_t) = z_2 (d_t^{\nu} k_t^{1-\nu})^{\gamma}, \tag{3}$$

$$q_t = q f_q(d_t, k_t) = q (d_t^{\mu} k_t^{1-\mu})^{\lambda}. \tag{4}$$

All parameters displayed in eq. (3) and (4) are strictly positive; moreover, ν and μ must be less than one in order to restrict the externality to non-negative values ($0 < \nu < 1$ and $0 < \mu < 1$). The vertical allocation of spillover is designed by γ and λ (*embodied vs. disembodied*) whilst ν and μ describe the horizontal assignment (*investment vs. consumption*). As a result, $\gamma\nu$ and $\lambda\mu$ measure the overall externality generated by ICT consumption on z_t and q_t; although, in light of the range of values admitted for the parameters, the externality can be also expressed in terms of firms' investment. It should be noticed that the spillover is rival either vertically or horizontally as its magnitude is assumed exogenous. For this reason, our model differs substantially from Bresnahan and Trajtenberg (1995) where the externality is endogenously feeded by the technological complementarity between producers and users of GPTs and, on the other side, the one existing among users of new technologies.

The key idea of the work is that, within an information society context, ICT consumption may yield some positive effects on productivity. This departs from the usual trade-off between current and future consumption postulated by most growth theories. To best of our knowledge, only Steger (2002) has studied how the traditional (intertemporal) trade-off changes in presence of a consumption enhancing the stock of human capital or the

[8]In line with the empirical estimates, the depreciation rate of ICT assets (δ) used at home and on the workplace is assumed identical (see Jorgenson and Stiroh (2000)).

marginal productivity of labor. This issue is central in the literature of development economics, where it is widely acknowledged the positive relation between nutrition (consumption) and labor productivity. According to Dasgupta and Marjit (2002), however, a similar dynamics may also arise for industrialized countries where people live better and, as a consequence, are likely to be more productive on the workplace.

Consumption and investment of ICT act as complementary factors in prompting the arrowian learning-by-doing in our framework. The belief is that the spillover is not exclusively determined by firms' investment but some other factors may contribute to the social value of capital. A similar role is attributed to aggregate consumption by Dasgupta and Marjit (2002) and to education by Greiner and Semmler (2002).

The problem of intertemporal optimization of household is to maximize the lifetime utility

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

with respect to c_{2t}, θ_t and l_t, subject to the constraints reported in (1) and (2); ρ (> 0) is the rate of time preferences. Solving the problem with the maximum principle, one has to impose the two following transversality conditions $\lim_{t\to\infty} k_t\phi_{1t} = 0$, $\lim_{t\to\infty} d_t\phi_{2t} = 0$ and assume positive values for the initial level of the state variables ($k_0 > 0$ and $d_0 > 0$)[9].

In the balanced growth path θ_t and l_t are time invariant (henceforth θ and l) whilst, as it will be shown below, the set of variables $\{c_{1t}, c_{2t}, y_{1t}, y_{2t}, k_t, d_t, z_{2t}, q_t\}$ grows at constant but different rates[10]. This is reason why Whelan (2003) argues that it would be more appropriate to be referred to as a steady-state growth path, provided that it is unbalanced towards durable goods. The issue of a balanced development is addressed more generally by Acemoglu and Guerrieri (2006); they show that it is not compatible with a balanced technological growth within a multi-sector framework in presence of capital deepening and different factor proportions. In our model, instead, both economic and technological growth are unbalanced because of the homogeneity imposed on the output elasticity to factor inputs.

It is possible to demonstrate that the state variables grow always at the same rate. As evident from eq. (1-4), this means that in steady-state any variable of the system can be expressed in terms of the growth rate of capital per labour unit (g_k). To our aims, however, it is more useful to express them

[9] A complete solution of the intertemporal problem is provided in the Appendix.

[10] Boucekkine *et al.* (2003) show that there is no transitional dynamics within a one-final sector economy.

as function of the labour productivity growth of ICT sector (g_2):

$$g_1 = \frac{1-\alpha}{1-\lambda} g_2, \quad g_k = g_d = \frac{1}{1-\lambda} g_2, \quad g_q = \frac{\lambda}{1-\lambda} g_2, \quad g_{z2} = \frac{\alpha - \lambda}{1-\lambda} g_2. \quad (5)$$

Therefore, in order to determine the equilibrium of the economy, it is sufficient to compute g_2:

$$g_2 = (1-\lambda)\big((1-\alpha) q z_2 (d_0/k_0)^\epsilon - \delta - \rho\big), \qquad \epsilon = \gamma\nu + \lambda\mu. \quad (6)$$

The knife edge condition on the overall entity of spillover ($\gamma + \lambda = \alpha$) leads the ICT sector to behave as in the AK model, exactly as depicted by Felbermayer and Licandro (2005). Nevertheless, our work departs from their model for two aspects. First, we admit that high-tech goods can be consumed, excluding thus the isomorphism with Boucekkine *et al.* (2003). Second, we identify the conditions under which there emerges a positive relation between embodied technological change and economic growth.

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

Assumption 1 $\quad (1-\alpha) q z_2 \big(d_0/k_0\big)^\epsilon > \delta + \rho.$

The economy-wide growth rate of labour productivity is calculated through the Divisia index's formula (see Whelan (2003)). It aggregates industries by means of the current output shares; 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 as too high weights are attributed to those goods featured by a marked decline in prices. US National Income and Product Accounts moved to chain aggregation in 1996, in conjunction with the introduction of hedonic pricing for ICT goods. In light of such a change, Whelan (2003) points out that the aggregation method adopted by GHK (1997) to check (and reject) the multi-sector representation of their economy is inadequate, as summing up outputs evaluated at base-year prices[11].

The identity of technology parameters across industries guarantees that the steady-state ratio of nominal outputs ($p_t y_{2t}/y_{1t}$) is time-invariant; as a consequence, also the sectoral shares remain constant along the equilibrium path ($\omega_i = p_{it} y_{it} / \sum_{i=1}^{2} p_{it} y_{it}$, $i = 1, 2$). This outcome makes the aggregate

[11] Acemoglu and Guerrieri (2006) consider final output as a fixed-year CES aggregation of two productions. Notice, instead, that a translog production function underlies the discrete time version of Divisia index (Tornqvist's index).

growth steady, albeit the discrepancy in industry growth rates. If the share of the faster growing sector was increasing, at a given time the traditional industry would disappear. Hence, the time-invariancy of industry shares is a necessary condition for the existence of the two-sector economy à la Whelan.

The chain aggregation rule is also utilized to estimate the economy-wide total factory productivity (g_z). We apply the method proposed by Domar (1961) and formally demonstrated by Hulten (1978); it 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 set-up, gross output equals value added, and thus Domar's and Divisia's weights coincide. The aggregate growth rate of labour and total factory productivity can be written as follows:

$$g_y = \omega_1 g_1 + \omega_2 g_2, \qquad g_z = \omega_1 g_{z1} + \omega_2 g_{z2}. \tag{7}$$

By employing eq. (5) and reminding that g_{z1} is zero, these rates can be finally reworded in terms of g_2:

$$g_y = g_2\big(1 - \frac{\gamma}{1-\lambda}\omega_1\big) = g_2 - g_{z2}\omega_1, \tag{8}$$

$$g_z = (1-\omega_1)g_{z2} = (1-\omega_1)\frac{\gamma}{1-\lambda}g_2. \tag{9}$$

Straightforwardly, ICT sector arises as the engine of the overall development ($g_1 < g_y < g_2$): the smaller the traditional production (ω_1), the higher the aggregate growth rate (g_y) as non-ICT sector expands at the expenses of innovative industry, which is the sole benefiting from increasing returns to scale. Moreover, the second expression for g_y in equation (8) illustrates how cross-industry dynamics is driven by a mechanism of transmission based on relative prices (neoclassic pecuniary spillover): a rise in TFP of ICT producers lowers g_p, encouraging firms to adopt cheaper and more efficient capital goods in both sectors. Yet, as above discussed, the largest low-tech sector, the least resources are available for ICT industry and opportunities for further advances diminish.

Productivity resurgence in the Information Age

Until the early 1990s the absence of correlation between IT investment and productivity fuelled the wisdom that information technology was unable to foster growth. Several explanations have been advanced for this puzzle. As above discussed, there was a change in the nature of technical progress that had not been fully understood. Also, the puzzle could be in part ascribed to statistical measurement problems: on one hand, the base-year volume indexes overestimated the ICT capital stock, on the other there was a systematic understatement of the real valued added of some intensively ICT-using industries (services). Finally, ICT required huge investments in complementary factors like business organization and workforce skills which confined to the long-run the related productivity gains[12].

As surveyed in Section 2, Boucekkine *et al.* (2003) interpret the advent of information technology in the 1970s as a shock triggering the embodiment process, modelled as a reassignment of the learning externality of capital. After 1973, the acceleration in the relative decline of investment goods' prices gave rise to a first wave of business investment in new technologies. Nevertheless, this asset type was unable to spur productivity which, by contrast, fell down due to the high obsolescence rate of new capital vintages. This was considered a cost inherent to the embodiment process.

In the mid-1990s however the United States sheered, switching to a high growth regime. The core of resurgence was the semiconductors market where the meaningful efforts in innovation activities materialized into marked efficiency gains. As intensively embodying such technologically advanced intermediate inputs, the production of ICT goods became more efficient as well; as a result, the new acceleration in the relative prices' fall stimulated the massive uptake of ICT by firms as well as households. It is only after 1995 that information technology has reached the critic threshold to foster the growth process (Cummins and Violante (2002)); as typical for any general purpose technology, this occurred several decades after its early penetration into the economy[13].

It is possible to demonstrate that, under the conditions reported in the following lemma, our model fits the US performance resulting from the information revolution of the mid-1990s. This shock has determined a further, stronger increase in the incorporated nature of technical change and, thus, similarly to Boucekkine *et al.* (2003) can be modelled as a reallocation of the learning externality of capital ($\Delta\lambda > 0$ and $\Delta\gamma < 0$).

Lemma 1 *The increase in the embodiment content of information technology* ($\Delta\lambda > 0$) *gives rise to an acceleration in the quality growth of ICT goods* ($\Delta g_q > 0$), *in the decline of relative prices* ($\Delta g_p < 0$) *and in 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] See respectively Oliner and Sichel (1994), Brynjolfsson and Hitt (2000) and Bresnahan *et al.* (2002).

[13] Jovanovich and Rousseau (2005) draw a close comparison between the diffusion of information technology and electrification.

- if $\mu > \nu$ $\frac{d_0}{k_0} > \frac{1}{(1-\alpha)z_2 q} e^{\frac{1}{\gamma(\mu-\nu)}}$;
- if $\mu < \nu$ $\frac{d_0}{k_0} < \frac{1}{(1-\alpha)z_2 q} e^{-\frac{1}{\gamma(\nu-\mu)}}$.

See the Appendix for the proof.

It is important to underline how these are the necessary conditions ensuring an upward jump in the aggregate TFP growth ($\partial g_z/\partial\lambda > 0$), but are also sufficient for an acceleration in GDP per employed ($\partial g/\partial\lambda > 0$); obviously, the behavior of g and g_z is driven by their industry counterparts (g_2, g_1 and g_{z2}). Lemma 1 imposes some boundary conditions to the ratio between the state variables at the initial time. d_0/k_0 must be higher than a given minimum level whenever the impact of spillover originating from ICT consumption is larger on q_t than z_{2t} ($\mu > \nu$). If the reverse holds ($\mu < \nu$), the ratio cannot overtake a certain upper threshold[14].

The mechanism at the basis of the speed-up in the development process has been extensively described above. It should be added that our model depicts comprehensively the growth impact of ICT[15]. In fact, both sectors contribute to the acceleration in labour productivity thanks to a more intensive ICT capital deepening (*adoption effect*). Furthermore, the upsurge in the aggregate TFP growth can be mainly traced to the relevant efficiency improvement of ICT producers (*production effect*). Last but not least, the economy takes advantage of an indirect external effect arising from the usage of ICT by firms and households (*spillover effect*).

4 Concluding Remarks

Information technology is widely acknowledged as the key factor behind the US productivity revival. By the mid-1990s ICT has revolutionized both firms' activity and household lifetime, delivering higher levels of efficiency and welfare.

This paper has proposed a model where the endogenous engine of growth is the learning-by-doing process associated to the usage of ICT at home and

[14] Since ICT goods devoted to production and consumption grow at the same rate, at any time the difference in the stock employed at home and on the workplace depends on their initial level. It is reasonable to believe that d_0/k_0 is smaller than the unity, as the economy by allocating more resources to production takes into a larger consideration future levels of wealth relatively to the current one. In this case ($d_0/k_0 < 1$), Lemma 1 remains valid only whether $z_2 q$ is sufficiently 'high' when $\mu > \nu$ and not too 'small' when $\mu < \nu$.

[15] Stiroh (2002a) provides an accurate description of the channels through which information technology may affect growth.

on the workplace. The advent of the Information Age has been described by means of a two-sector framework (à la Whelan) that, distinguishing between ICT producers and users, fits the recent growth performance of the United States.

Around 1995, the extraordinary upsurge in semiconductors' efficiency raised the incorporated nature of progress, making new capital assets enormously more productive. The productivity growth in ICT industry pushed relative prices down, enabling the global diffusion of new technologies throughout the economy. Finally, the resurgence in labour and total factory productivity is entirely ascribable to the faster ICT capital deepening, TFP growth of ICT producers and the spillover effects determined by the deployment of information technology.

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Appendix

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

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

Replacing c_{1t} with $y_{1t} = ((1-\theta_t)k_t)^{1-\alpha} l_t^{\alpha}$, 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:

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

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

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

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

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

Also, we need 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 steady-state the variables of the system $\{c_{1,t}, c_{2,t}, y_{1,t}, y_{2,t}, k_t, d_t, z_{2,t}, q_t\}$ grow at constant (even though different) rates and the inputs shares $\{\theta_t, l_t\}$ are time invariant (hereinafter θ and l).

The latter condition implies that the time log-derivative of the production function of the traditional sector is $g_1 = (1-\alpha)g_k$. Then, once exploited the equilibrium equality $g_{c2} = g_i$ that arises from the budget constraint of ICT sector ($y_{2t} = c_{2t} + i_t$), from the two accumulation laws durable goods turn out to grow at the same rate ($g_k = g_d$). This outcome allows us to formulate the embodied and disembodied technical change as $g_q = \lambda g_k$ and $g_{z2} = (\alpha-\lambda)g_k$. Finally, the latter expression (g_{z2}) can be employed to compute the labour productivity growth rate of ICT industry ($g_2 = (1-\lambda)g_k$). Now any variable of the system can be expressed in terms of g_2[16].

[16] See eq. (5) within the main text.

In order to obtain g_2, preliminarily one has to substitute $g_q = g_2\,\lambda/(1-\lambda)$ into the time log-derivative of the first FOC ($\partial H(.)/\partial\theta$):

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

$-\dot{\phi}_{1t}/\phi_{1t}$ can be easily calculated by replacing the expression for ϕ_{1t} resulting from $\partial H(.)/\partial\theta$ into $\partial H(.)/\partial k$, after having divided 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 $\theta = 1 - l$, that arises by the ratio between $\partial H(.)/\partial\theta$ and $\partial H(.)/\partial l$. This means that each sector employs labour and capital inputs in the same proportions.

At this point, it is sufficient to replace $-\dot{\phi}_{1t}/\phi_{1t}$ into g_2 and take into consideration the explicit expression for q_t and z_{2t}:

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

g_2 is thus shaped as d_t/k_t has been reworded in terms of their initial time values, provided that $g_d = g_k$. Labour productivity growth of ICT industry is positive under the Assumption 1 displayed in the main text.

By means of easy algebra, it is also possible to verify that the transversality conditions are satisfied. In fact, replacing ϕ_{1t} stemming from the first FOC into $\lim_{t\to+\infty} k_t\phi_{1t}$, and expressing the variables in terms of g_k, it can be seen that the limit goes to zero when $\rho > 0$[17]; but this condition is true by assumption. The same holds for the second transversality condition.

Proof of Lemma 1

As a preliminary step we have to show that industry output shares (ω_{it}) are always constant. This depends on the invariancy of $p_t y_{2t}/y_{1t}$ with respect to time and the information shock ($\Delta\lambda > 0$):

$$\frac{\dot{p}_t}{p_t} + \frac{\dot{y}_{2t}}{y_{2t}} - \frac{\dot{y}_{1t}}{y_{1t}} = -\frac{\dot{z}_{2t}}{z_{2t}} + \frac{\dot{y}_{2t}}{y_{2t}} - \frac{\dot{y}_{1t}}{y_{1t}} = -\frac{\alpha-\lambda}{1-\lambda}g_2 + g_2 - \frac{1-\alpha}{1-\lambda}g_2 = 0,$$

$$\frac{\partial p_t}{\partial\lambda}\frac{y_{2t}}{y_{1t}} + p_t\frac{\partial y_{2t}}{\partial\lambda}\frac{1}{y_{1t}} - p_t y_{2t}\frac{1}{(y_{1t})^2}\frac{\partial y_{1t}}{\partial\lambda} = -\frac{1}{(z_{2t})^2}\frac{\partial z_{2t}}{\partial\lambda}\frac{y_{2t}}{y_{1t}} + \frac{1}{z_{2t}}\frac{y_{2t}}{z_{2t}}\frac{\partial z_{2t}}{\partial\lambda}\frac{1}{y_{1t}} + 0 = 0.$$

[17] This happens since all the exponential terms relative to the state variables sum up to zero.

The former outcome exploits eq. (5), the latter the definition of relative prices ($p_t = -1/z_{2t}$) and the fact that y_{2t} changes in response to a variation in λ through z_{2t}, while y_{1t} remains constant.

Consider now the simplified version of the aggregate growth rate of labour and total factory productivity resulting from eq. (8-9), where $\chi = \gamma/(1-\lambda) = (\alpha - \lambda)/(1-\lambda)$:

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

A 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:

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

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

Since $\partial\chi/\partial\lambda$ is less than zero, the right-side term is negative in the first expression and positive in the second one; as a consequence, $\partial g_y/\partial\lambda > 0$ 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 $\kappa = (\mu - \nu)\ln((1 - \alpha)qz_2(d_0/k_0))$. Finally $\partial g_z/\partial\lambda > 0$ can be reworded as follows:

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

We have certainty that this inequality is verified when $\kappa > 1/\gamma$, i.e. under the conditions reported in Lemma 1.