Learning-by-Doing, Hi-Tech Consumption and Productivity Resurgence

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Abstract

This paper presents a growth model where the technological externality (*learning-by-doing*) generated by ICT is the key mechanism for development.
If hi-tech assets are able to engender increasing returns, as being knowledge (or R&D) based or because creating network externalities, then the economy benefits from total spending on ICT goods, both for productive and consuming aims.
Therefore, hi-tech consumption may emerge as a complementary source (with respect to investment) of growth in the industrialized countries as, here it is shown, for the U.S. productivity resurgence of the mid-Nineties.

Keywords: IT investment and consumption, learning-by-doing, labor productivity and TFP resurgence.
JEL: E21, E22, E32, O41, C61.

1 Introduction

In the mid-Nineties the United States entered a New Economy age featured, on the one hand, by the acceleration in GDP and productivity growth and by low unemployment and inflation, on the other.

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A key role has been played by Information and Communication Technologies (ICT). These assets have massively spread throughout the economy as a result of the sharp decline in prices, owing to the collapse in semiconductors cost.[1]
In 1995 the changeover from a three- to a two-year product cycle of chips provoked a 90% fall in prices; thus, goods incorporating semiconductors as intermediates inputs have become more efficient and less expensive (Jorgenson (2001)).
Hi-tech capital deepening (per capita investment on computer, communication equipment and software) and the increased efficiency of ICT-producing industries accounted for the entire one percent acceleration in GDP per hour between 1973-95 and 1995-2001.[2]
Labor productivity has steadily switched to a high-growth regime (Kahn and Rich (2003)) so to dispel every residual doubt of skeptics on the role of Information Technology as permanent source of growth (see Gordon (2003a)). The IT impact is now widely regarded as a structural rather than a cyclical phenomenon of the U.S. experience as, by contrast, it was argued for a long time.

The fall in prices, the higher disposable income, the strong trust of Americans on the New Economy have led hi-tech demand of households to rise, too.[3]
As figure 1 shows, from the mid-Nineties on the weight of computer (Pc) on personal consumption (PCE) and consumer durables (Dur.) expenditure has been continuously increasing.
Jorgenson and Stiroh (2000) find out that consumers' purchases of computer and software accounted for one fifth of the 1% contribution of ICT to output growth between 1995 and 1998 (4.5% per year).[4]

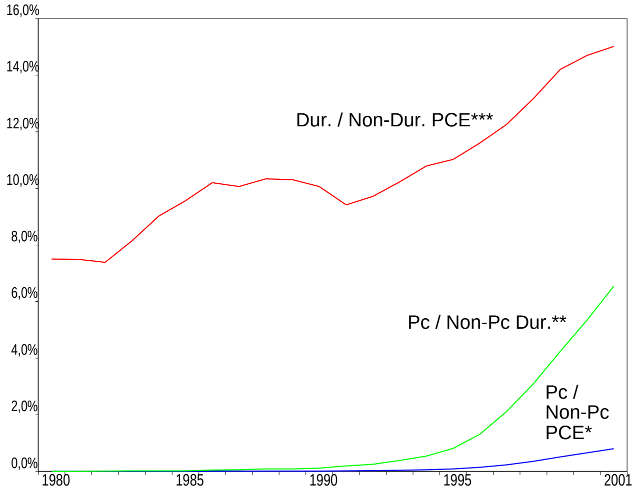
[1]Bresnahan and Trajtenberg (1995), p. 84, consider semiconductors, similarly to steam engine and electricity, as General Purpose Technologies (GPT) because they "...are characterized by the potential for pervasive use in a wide range of sectors (from computers to cars; N.o.A.) and by their technological dynamism".

[2]See data by Gordon (2003b) reported in table 1. Moreover, for the U.S. case see Oliner and Sichel (2000), Jorgenson (2001), Jorgenson *et al.* (2003). For a comparison between the U.S. and the E.U. and among European member countries see Daveri (2003), van Ark *et al.* (2002) and Timmer *et al.* (2003).

[3]See Gordon (2003b) for a brief description of the virtuous circle featuring the U.S. economy in late Nineties (high growth, Nasdaq's bubble, low inflation, inflows of foreign investments, etc.).

[4]These auctors adopt the production possibilities frontier approach introduced by Jorgenson (1966) and Jorgenson and Griliches (1967) in their growth accounting studies. The income growth is decomposed into a weighted average of real growth rates either of consumption and investment goods (output side) or labor and capital inputs (input side). The shares of outputs and inputs on nominal income are used as weights.

Figure 1: **U.S. Personal Consumption Expenditure 1980-2001** (values in 2000 real dollars)



Source: NIPA, U.S. Bureau of Economic Analysis.
* ratio between real expenditure on Pc and total consumption expect computer;
** ratio between real expenditure on Pc and durable goods except computer;
*** ratio between real expenditure on durable goods and total consumption except durables.

So far no attention has been devoted to the role of hi-tech consumption on development as ICT have been secondary on households' spending.
Nevertheless, it is reasonable to question whether the domestic stock of hi-tech goods can perform as a complementary source of modern growth, especially if consumption trend continues in next years.
Investment is straightforwardly the main factor for development because it makes up the productive capacity of the economy; however, it may be useful to look at how people allocate time and resources between traditional and hi-tech goods because of their different features.
ICT and low-tech goods differ by their own *nature*: the former gradually release their utility content and, to a broad extent, behave as capital assets. In addition, by *aim*, as durables satisfy upper rather than basic needs of people (cultural, entertainment and so forth).
Moreover, ICT goods are more R&D intensive and contribute to enlarge the stock of knowledge of the economy (by *content*); in this respect, allocating more resources to hi-tech with respect to traditional goods, households can afford higher levels of welfare in the long run.[5]

[5]The logic of this paper is very close to Balducci (2003) that introduces public consumption into the households' utility function in the well-known framework developed by

Finally, certain kinds of New Technologies such as communication devices create network externalities by their own nature: the economic system benefits from the increasing number (and spending) of people dealing with these assets.
Hence, the economic performance of industrialized countries may also diverge because of a different propensity towards hi-tech consumption. A society well-disposed to innovative goods is likely to build lower cultural and professional barriers to the adoption of New Technologies on the workplace; therefore, it is able to fully exploit their growth potential.

This paper presents a growth model where the adoption of hi-tech goods both on the production- and domestic-side is the key factor for development:[6] ICT are supposed to generate a technological spillover that derives from the learning-by-doing process.
In this respect, the U.S. productivity resurgence of the mid-1990s is shown to be due to a deeper penetration of ICT through all the economy.
Only from 1995 onwards, the stock of knowledge based capital is likely to have reached a such level to engender a technological spillover able to accelerate the growth rate.

The remainder is organized as follows. Section 2 summarizes the debate prompted by Solow (1960) and Jorgenson (1966) on the impact of technical progress on economic growth (*the embodiment controversy*).
On the one hand, scientific advances are imagined to hit the economic efficiency (TFP) in a neutral (or pervasive) way, without changing the marginal contribution of factors (*disembodied technical change*).
One the other hand, progress is supposed to affect only on the productivity of new vintages of capital (*embodied technical change*).
Once surveyed those contributions acknowledging a *productive* role for consumption, section 3 analyzes the growth-enhancing impact of domestic accumulation of ICT (and other durables).

In conclusion, it will be evident that the findings depend neither on the framework taken into account (aggregate vs. multi-sector economy) nor on the hypotheses on nature of progress (disembodied vs. embodied).
This is the reason why looking at hi-tech consumption may be helpful in shedding more light on the sources of modern growth (section 4).

Barro (1990). Households are able to reach the optimal level of welfare with less resources; the surplus can be invested and, consequently, the economy grows faster.

[6] According to Quah (2002) and Petit and Soete (2001), ICT are likely to improve both the efficiency in production (supply-side effect) and the employability of people using New Technologies at home with respect to non-ICT-consuming workers (demand-side effect).

2 Technical Progress and Growth

Technology has been always acknowledged as a primary source of growth. Nevertheless, there is no consensus on the way it impacts on economic activity (*the embodiment controversy*).
This debate goes back to the Sixties and has been recently revived by the number of studies on the productivity resurgence.[7]

Solow (1957) defines technical change (z_t) as the residual growth of output not explained by the change in factors (Total Factory Productivity, TFP); so, z_t measures the improvement in production efficiency gained over the time:

$$Y_t = z_t F(K_t, L_t). \tag{1}$$

Technology hits the economy in a (*Hicks-*) *neutral* way because it does not modify the marginal rate of inputs substitution; consequently, progress is *disembodied*.
Despite the intuitive meaning and easy computation, this approach presents some drawbacks.[8]
First, if the *true* progress is not neutral but biased towards a more intensive use of any input ($y_t = f(a_t K_t, b_t L_t)$, $a_t \gtreqless b_t$), z_t consists in a weighted average of factor-specific technical changes:

$$\frac{\dot{z}_t}{z_t} = s_t^K \frac{\dot{a}_t}{a_t} + s_t^L \frac{\dot{b}_t}{b_t}. \tag{2}$$

In this case, the *measured* growth of residual can be due to a change in inputs share (s_t^K or s_t^L) rather than an *effective* shift of production function.
If applied to a parametric function, the residual picks up every effect due to the bad specification of model (omitted variables, measurement errors, imperfectly competitive markets, increasing returns and externalities) so that

[7] Two theories are at variance: on the one hand, the *neoclassic* approach (*growth accounting*) regards technical change basically as disembodied. On the other hand, *dynamic general equilibrium* (DGE) models treat it as incorporated.
As the reading of this section will make it clear, these views reflect the difference in their analytical instruments and scientific goals.
Based on Solow (1957), growth accounting links changes in output to the ones in factors, measuring accurately input-specific contributions to growth.
DGE models are deeply based on the growth theory, describing either the structure of the economy or the accumulation of inputs. This is the reason why they are able to foresee the effects of technological shocks by simulations.
Growth accounting looks at the past, DGE models at the future (Bakhshi and Larsen (2001)).

[8] See Hulten (2000) for an exhaustive description of virtues and drawbacks of total factory productivity.

z_t is unfit to represent technological advances.
Second, (1) mainly reflects a quantitative (or process-oriented) concept of progress that shifts the production function outward. Quality improvement of goods and households' loving for variety are not contemplated so that TFP can be interpreted as a rough index of welfare.
Finally, Hicks-neutral progress neglects that the economy develops only when it invests on new vintages of capital goods incorporating innovations.
Investment is the key mechanism for development and, more importantly, it has to be measured in *effective* or *quality adjusted* units ($q_t I_t = I_t^*$; embodied -Solow (1960)- or investment-specific technical change, -Greenwood *et al.* (1997)-):

$$Y_t = F(K_t, L_t) = C_t + I_t \tag{3}$$
$$\dot{K}_t = I_t^* - \delta K_t.$$[9]

By contrast Jorgenson (1966) argues that the growth accounting is not able to solve the embodiment controversy because there is a one-to-one correspondence between z_t and q_t. The indexes of neutral and embodied technical change in practice coincide.[10]
It would be sufficient to provide the economy with a multi-sector representation featured by a TFP-efficiency of equipment producers growing faster than in other industries.
Hercowitz (1998) points out that Jorgenson fails in considering consumption and investment goods (in physical units) as perfect substitutes because of the inadequacy of resulting framework:

$$Y_t = F(K_t, L_t) = C_t + I_t^*. \tag{4}$$

As perfect competition forces q_t to 1 ($\partial I_t / \partial C_t = \partial \frac{I_t^*}{q_t} / \partial C_t = 1/q_t = 1$), (4) excludes investment-specific technical change, implying a stability of relative prices that does not fit the declining trend of the last decades.[11]

[9] q_t puts vintages, differing in the content of technology they incorporate, onto a common ground based on their *effective* contribution to output. In the following it will be shown that q_t represents the obsolescence effect deriving from technical advances of investment goods.
δ gauges the difference in efficiency between older and new vintages, due to the loss of productive capacity (*wear and tear*; Hulten (1992), p.965).

[10] It can be demonstrated that z_t picks up every unmeasured quality improvement of inputs (represented by q_t). Moreover, since it does not modify the relative use of inputs in the production of capital goods, q_t is neutral by its own nature.

[11] According to Ho and Stiroh (2001) and Oulton (2004), eq. (4) does not reflect Jorgenson's thought, so no conclusion on the *embodiment controversy* can be drawn from it.

If it is dealt with embodied technical change, Hulten (1992) states that both investment ($I_t^* = q_t I_t$) and capital ($J_t = \varphi_t K_t$) quality improvement must be taken into consideration and output must be measured in effective units (O_t vs. Y_t).
In this case the production possibilities frontier[12] can be written as

$$(1-w_t)\frac{\dot{C}_t}{C_t} + w_t\Big(\frac{\dot{q}_t}{q_t} + \frac{\dot{I}_t}{I_t}\Big) = \frac{\dot{O}_t}{O_t} = (1-v_t)\frac{\dot{L}_t}{L_t} + v_t\Big(\frac{\dot{\varphi}_t}{\varphi_t} + \frac{\dot{K}_t}{K_t}\Big) + \frac{\dot{\lambda}_t}{\lambda_t},$$

where λ_t is the *true* index of Hicks-neutral technology.
The correspondence between λ_t and the residual of the neoclassical framework (eq. (1))

$$\frac{\dot{z}_t}{z_t} = v_t\frac{\dot{\varphi}_t}{\varphi_t} - w_t\frac{\dot{q}_t}{q_t} + \frac{\dot{\lambda}_t}{\lambda_t}$$

is guaranteed only if the first two terms of this identity balance.[13] Hulten (1992) finds out that this condition held in the U.S. case for a long time (through the early Eighties). Therefore, the technological performance was correctly inferred by looking at the residual ($\frac{\dot{z}_t}{z_t} \simeq \frac{\dot{\lambda}_t}{\lambda_t}$).

Criticism on Hicks-neutral view of technology became very fierce with the long-lasting age of *productivity slowdown*; since the mid-Seventies TFP showed a sluggish dynamics despite the massive investments on ICT assets. This puzzle increasingly led to consider the residual as an unsatisfactory index of progress: *despite* the adoption of robot, computer, etc. by firms, the invariancy of TFP revealed that *no relevant innovations* were disseminating throughout the economy (Greenwood and Jovanovic (1998), p.8).
Accordingly, Greenwood, Hercowitz and Krusell (1997) (hereinafter GHK) find out a secondary role of disembodied technical change in the U.S. postwar growth, once introduced the Hicks-neutral technology in Solow (1960) and distinguished capital between equipment (K_e) and structures (K_s)

$$Y_t = z_t F(K_{s,t}, K_{e,t}, L_t) = C_t + I_{s,t} + I_{e,t}$$

$$\dot{K}_{e,t} = q_t I_{e,t} - \delta_e K_{e,t}$$
$$\dot{K}_{s,t} = I_{s,t} - \delta_s K_{s,t}.^{14}$$

[12]See footnote 4.

[13]This happens when the growth of effective capital is totally offset by the obsolescence caused by the quality improvement of investment goods.

[14]$K_{e,t}$ is the only asset enjoying a quality improvement due to innovation (*via* q_t). As the index of embodied technical change (q_t) indicates how much *quality adjusted* capital can be bought by investing one unit of physical output, then $\frac{1}{q_t}$ represents the relative price between capital and consumption goods.

Table 1: **The sources of the U.S. productivity performance** (average growth rates, % points)

		1973-1995 (1)	1995-2001 (2)	Post-1995 Change (2-1)
Labor Productivity	(a=b+c+d)	**1,40**	**2,25**	**0,85**
Capital Deepening	(b)	**0,71**	**1,17**	**0,46**
IT capital	(b1)	0,42	0,97	0,55
other capital	(b2)	0,30	0,20	-0,10
Labor Quality	(c)	**0,27**	**0,25**	**-0,02**
Total Factor Productivity:	(d)	**0,42**	**0,83**	**0,41**
IT-producing industries	(d1)	0,30	0,73	0,43
other industries	(d2)	0,12	0,10	-0,02
memo: total IT contribution	(b1+d1)	**0,72**	**1,70**	**0,98**

Source: Gordon (2003b)

In this way, *embodied* and *neutral* progress are calculated to have respectively contributed for a 60 and 40% to output per capita growth.

These findings (and the underlying methodology) have been straightforwardly debating by the number of (multi-sectoral) studies on the recent TFP resurgence (0.83%; see table 1).
These works disentangle the aggregate productivity into industry-specific contributions, revealing that ICT-producing sectors accounted for almost the entire post-1995 TFP growth (0.73 vs. 0.10%).[15]

In conclusion, this survey on the *embodiment controversy* shows that the competing theories differ more on the way of representing the economy than the impact of technical change. Indeed, growth accounting and DGE models share the belief that the increasing efficiency of equipment has been (and will be) central for recent (and future) growth.
DGE models are *forced* to explicitly introduce a quality index to grasp the

So, it is possible to infer on relative quality improvement (the embodied nature of progress) by looking at prices ($p_t = \frac{1}{q_t}$).
Moreover, Hercowitz (1998), p.223, disentangles $\frac{\dot{q}_t}{q_t}$ into a *direct* effect that represents the output growth depending on quality improvement given the level of investment (38%) and an *indirect* effect deriving from the acceleration in capital accumulation due to increasing quality of investment (22%).

[15] These works are listed in footnote 2. The technique used in these studies was proposed by Domar (1961) and it will summarized in Sect. 3.5.

improvement in capital goods as dealing with an aggregate (or one-sector) framework.
Nevertheless, similar results may emerge in a multi-sector setting if hi-tech goods producing industries (equipment or durable) are endowed with a more efficient (Hicks- neutral) technology (Jorgenson (1966)) or labor input (Ortigueira (2003)).[16]

3 Hi-Tech Consumption and Economic Growth

3.1 The Productivity Slowdown Age (1973-95)

The *slowdown age* was featured by massive investments on New Technologies due to the sharp decline in relative prices in post-oil crisis but with no effects on productivity performance, despite the higher efficiency of IT assets.
Boucekkine, Del Rio and Licandro (2003) show that, in an economy *à la GHK* (that is featured by the cohabitation between z_t and q_t):

$$y_t = z_t f(k_t) = z_t k_t^{1-\alpha} \qquad 0 < \alpha < 1,$$

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

this picture emerges from the reallocation of capital spillover from consumption (z_t) to investment efficiency (q_t) stemming from the introduction of Information Technology ($\Delta\lambda > 0$).

$$z_t = z k_t^{\gamma} \qquad z > 0, \qquad 0 < \gamma < 1,$$

$$q_t = q k_t^{\lambda} \qquad q > 0, \qquad 0 < \lambda < 1.^{17}$$

New Technologies reinforced the *incorporated* nature of progress ($\Delta\lambda > 0$),[18] speeding up the quality improvement of investment goods ($\Delta\frac{\dot{q}_t}{q_t} > 0$). As a result, the expansive role of spillover was cancelled out by the acceleration

[16]Moreover, the wider use of hedonic deflators in National Accounts induces to correctly gauge the effective (or quality adjusted) contribution of factors to output; so, the embodied technology in capital assets is now taken into account more accurately (Schreyer (2002), p.29, and Bassanini and Scarpetta (2002)).
These aspects tend to fill the gap between DGE models and the neoclassic approach in the debate on the link between progress and development.

[17]Total efficiency equals the labour share on income ($\alpha = \gamma + \lambda$).

[18]Since α is fixed, $\Delta\lambda > 0$ implies $\Delta\gamma < 0$: the embodiment induces to a simultaneous reduction of Hicks-neutral efficiency.

of the obsolescence.[19]
This is the reason why labor productivity (g)

$$g = \frac{\dot{y}_t}{y_t} = \frac{1}{\hat{\sigma}}((1-\alpha)zq - \delta - \rho), \qquad \hat{\sigma} = \sigma + \frac{\lambda}{1-\lambda},$$

slowed down ($\frac{\partial g}{\partial \lambda} < 0$).
Deflation ($\Delta\frac{\dot{p}_t}{p_t} = -\Delta\frac{\dot{q}_t}{q_t} < 0$) and TFP deceleration ($\Delta\frac{\dot{z}_t}{z_t} < 0$) completed the macroeconomic picture caused by the dissemination of ICT among firms from the early Seventies onwards.

3.2 Traditional vs. Productive Consumption

Neoclassic and New Growth Theories have always regarded consumption as a growth-slowing factor[20] because it reduces saving and, consequently, accumulation (*traditional* trade-off between current and future consumption).

So far only development economists have described a different dynamics from the mainstream. Looking at poor countries featured by problems of nutrition, they find out that an increase in consumption usually boosts both labor productivity and output growth.
Steger (2002) formalizes this mechanism in a growth framework in order to check how the *traditional* trade-off changes when consumption positively affecting on human capital stock or marginal productivity of labor (*productive* consumption).

Dasgupta and Marjit (2002) argue that a positive correlation between consumption and growth may also emerge in industrialized countries.
Advanced economies can afford to allocate more resources to consumption; so, people reach higher levels of welfare because they can spend money to satisfy both basic (food, health and education) and upper needs (cultural, entertainment, etc.). Western countries inhabitants live better and are more productive on the workplace.
In Dasgupta and Marjit's framework, the growth rate of the economy depends on two competing forces: the usual relation among consumption, saving and accumulation (the *traditional* trade-off) and a new one picking up the consumption externality on marginal labor productivity (*à la Sheshinsky effect*). In presence of decreasing marginal returns, consumption is able sustain growth

[19] If obsolescence was exogenous as in Greenwood *et al.* (1997), it would reduce marginal productivity of capital. Here, it depends on capital accumulation so to partly offset the propensity to save of households: the *effective* intertemporal substitution rate is higher than when obsolescence is exogenous ($\hat{\sigma} > \sigma$).

[20] The most notable exception is Grossman and Helpmann (1991).

upto a certain level; beyond this, the *traditional* trade-off becomes dominant again. Finally, an U-inverted relation between consumption and growth emerges.[21]

Dasgupta and Marjit (2002) consider consumption as homogenous and neglect any qualitative difference among goods. In this respect they do not fit modern consumer habits: households buy items that differ for duration, knowledge content and the kind of needs they satisfy.
In developed countries increasing shares of consumption expenditure are devoted to durables (figure 1). These items are more knowledge intensive than traditional ones (clothing, foods, etc.) and, in essence, they meet upper needs of people.
Moreover, among durables, a wider variety of hi-tech goods, both new items (mobile phones and Pc) and existing ones, renewed by the embodiment of electronic components (satellite TV, car, household appliances), are now available at lower prices thanks to the progress of Information Technology.

In the following, in order to take in the right consideration the new spending behavior of households, high-tech consumption will be introduced in the aggregate framework developed by Boucekkine *et al.* (2003).

3.3 Hi-Tech consumption and Learning-by-Doing in an Aggregate Economy (one-final-sector model)

A representative infinitely lived household is supposed to buy traditional (c_t) and hi-tech goods (d_t).
The former are instantaneously consumed; the latter gradually release their utility content so to be very close to equipment adopted in production.[22]
Households own firms so to allocate resources between traditional consumption and a broadly intended capital (k_t) that can be exploited both for domestic (θ_t) and productive ($1 - \theta_t$) aims.
Hence, $d_t = \theta_t k_t$ represents durables bought by households as consumers, $e_t = (1 - \theta_t)k_t$ equipment acquired as firms' owners.

Labor supply is exogenous, there is no demographic dynamics and variables are measured in effective units so that the log-utility can be written

[21] Dasgupta and Marjit (2002) adopt a Harrod-neutral technology depending on both *aggregate* capital and consumption. In a competitive world, households do not fully understand the role of consumption; therefore, an intervention of the benevolent planner is required to avoid a balanced growth path featured by over-accumulation.

[22] Jorgenson and Stiroh (2000), p.187.

as

$$u(c_t, d_t) = u(c_t, \theta_t k_t) = \psi \log(c_t) + (1-\psi)\log(\theta_t k_t).^{23}$$

ψ is the relative weight ($0 < \psi < 1$) of traditional goods.

The competitive economy is featured by constant returns to scale and α ($0 < \alpha < 1$) is the labor share on income

$$y_t = z_t f(e_t) = z_t[(1-\theta_t)k_t]^{1-\alpha},$$

$$\dot{k}_t = q_t i_t - \delta k_t.$$

δ ($0 < \delta < 1$) is the depreciation rate, z_t is the residual TFP and q_t the solowian quality index of investment.

i_t is the wide-intended investment. It represents the resources that are not consumed in traditional way but devoted to the accumulation of knowledge intensive goods (equipment and consumer durables).

The efficiency indexes of final production and capital accumulation (z_t and q_t) are endogenous; they depend on knowledge and technological spillover generated by capital (hereafter simply *learning-by-doing*).

As in Boucekkine *et al.* (2003) the learning elasticities (γ and λ) sum to α (constant).

Since k_t has two different aims, it has to be specified how much efficiency depends on (share of) capital used at home (θ_t) and on the workplace ($1-\theta_t$). So, ν and μ express their relative weights on z_t and q_t:

$$z_t = z[d_t^{\nu} e_t^{1-\nu}]^{\gamma}, \tag{5}$$

$$q_t = q[d_t^{\mu} e_t^{1-\mu}]^{\lambda}. \tag{6}$$

$0 < \nu < 1$ and $0 < \nu < 1$, z and q are positive parameters.

On the one hand, γ and λ express how externality is exogenously distributed

[23] In this aggregate framework durables and equipment are the two sides of the same coin ($d_t = \theta_t k_t$) because there is only one state variable (k_t). I would like to thank Raouf Boucekkine for this suggestion.

The usual distinction between d_t and k_t as state variables will be reintroduced later in a multi-sector framework.

In order to understand the core of the analysis, the reader should imagine that buildings (dwellings and non-residential structures) are not included in the choice problem.

Moreover, in the following, the dichotomies *durables vs. non-durables* and *ICT vs. non-ICT goods* will be used as synonymous. The former is more general but the latter is more appropriate when it is dealt with deflation that, in particular, features computers (and few other categories such as audio, video, etc).

When adopting the former (durables *vs.* non-durables), it must be kept in mind that the international classification of consumption goods includes among durables some items that cannot be strictly considered as hi-tech (furnishings, furniture, etc.), especially if compared to the R&D content of some non-durables (such as pharmaceutical products).

between production and accumulation so to represent the *vertical allocation* of spillover. On the other, ν and μ describe the *horizontal* assignment. Consequently, $\gamma\nu$ and $\lambda\mu$ measure the *effective spillover* generated by hi-tech consumption on z_t and q_t.

Since α is *given* and *rival* both vertically and horizontally, the dichotomic representation of spillover presented in this paper clearly differs from the one provided by Bresnahan and Trajtenberg (1995).
They have two *distinct* externalities in a multi-sector framework, both *endogenously* depending on the technological complementarity between *producers* and *users* of General Purpose Technologies (GPT)[24]: both kinds of firms have profits increased whenever someone innovates (vertical externality).
Furthermore, every user takes an advantage from the expanding number of buyers as it enhances the effort in GPT innovation (horizontal externality).

In the present work, high-tech consumption and capital are regarded as complementary factors in prompting the arrowian learning-by-doing.
In this respect, d_t behaves similarly to the aggregate consumption in Dasgupta and Marjit (2002) and to (the share of) education in Greiner and Semmler (2002). These studies share the belief that the spillover does not only depend on the investment story but other factors may matter for the social contribution of capital (quality of life, education, hi-tech consumption, etc.).

The intertemporal problem is solved by the Hamiltonian function

$$H(.) = u(c_t, \theta_t k_t)\ e^{-\rho t} + \phi_t\{q_t y_t - q_t c_t - \delta k_t\}, \tag{7}$$

where ρ (> 0) represents the intertemporal discount factor and ϕ_t the costate variable associated to k_t.
The first-order maximum conditions are:

$$\frac{\partial H(.)}{\partial c_t} = 0 \quad \Rightarrow \quad u^{'}_{c_t}\ e^{-\rho t} = \phi_t\ q_t, \tag{8}$$

$$\frac{\partial H(.)}{\partial \theta_t} = 0 \quad \Rightarrow \quad u^{'}_{\theta_t}\ e^{-\rho t} = -\phi_t\ q_t\ y^{'}_{\theta_t}, \tag{9}$$

$$\frac{\partial H(.)}{\partial k_t} = -\dot{\phi}_t \quad \Rightarrow \quad -\dot{\phi}_t = u^{'}_{k_t}\ e^{-\rho t} + \phi_t\ \left(q_t\ y^{'}_{k_t} - \delta\right); \tag{10}$$

$k_0 > 0$ is the initial value of the stock variable and $\lim_{t\to+\infty} k_t\phi_t = 0$ the usual transversality condition.
The partial derivatives of utility function with respect to its arguments are

$$u^{'}_{c_t} = \frac{\psi}{c_t}, \quad u^{'}_{\theta_t} = \frac{1-\psi}{\theta_t}, \quad u^{'}_{k_t} = \frac{1-\psi}{k_t};$$

[24]See footnote 1.

for the production function we have

$$y'_{\theta_t} = -(1-\alpha)\frac{y_t}{1-\theta_t}, \quad y'_{k_t} = (1-\alpha)\frac{y_t}{k_t}.$$

In the Balanced Growth Path (BGP) the variables $\{y_t,\, c_t,\, i_t,\, k_t,\, z_t\;\, q_t\}$ grow at a constant rate and θ_t is time invariant (hereafter θ).
The log-derivative with respect to time of (8) yields

$$\frac{\dot{c}_t}{c_t} = -\frac{\dot{\phi}_t}{\phi_t} - \frac{\dot{q}_t}{q_t} - \rho. \tag{11}$$

$-\frac{\dot{\phi}_t}{\phi_t}$ can be obtained dividing (10) by ϕ_t and, then, replacing in the right side of this expression ϕ_t that stems from (9):

$$-\frac{\dot{\phi}_t}{\phi_t} = (1-\alpha)q_t z_t[(1-\theta)k_t]^{-\alpha} - \delta. \tag{12}$$

It is apparent that the shadow price of state variable moves at a higher rate with respect to the traditional case (no capital for domestic aims) because, now, only a fraction of capital is devoted to production. Therefore, its marginal productivity declines more slowly.[25]

In *steady-state* c_t and y_t grows at the same rate g. Then, it is possible to substitute $-\frac{\dot{\phi}_t}{\phi_t}$ and $\frac{\dot{q}_t}{q_t} = \frac{\lambda}{1-\lambda}g$ in (11). The latter derives from (6) once the *steady-state* relation between capital and output $\left(\frac{\dot{k}_t}{k_t} = \frac{1}{1-\lambda}g\text{, from the production function}\right)$ has been exploited.

$$g = (1-\lambda)\big((1-\alpha)q_t z_t[(1-\theta)k_t]^{-\alpha} - \delta - \rho\big).$$

Finally, in order to obtain the output per capita growth rate, the explicit expressions for z_t and q_t $\big($eq. (5) and (6)$\big)$ have to be replaced in the previous equation

$$g = (1-\lambda)\{A - \delta - \rho\},$$

where

$$A = (1-\alpha)qz(\frac{\theta^*}{1-\theta^*})^{\epsilon}, \qquad \epsilon = \gamma\nu + \lambda\mu. \tag{13}$$

ϵ is the total externality generated by hi-tech consumption on the economy;

$$\frac{\theta^*}{1-\theta^*} = \frac{1-\psi}{\psi}\frac{c_0/y_0}{1-\alpha}$$

[25] $-\frac{\dot{\phi}_t}{\phi_t} = q_t\frac{MPK}{(1-\theta)^{\alpha}} - \delta$; MPK is marginal productivity of capital in the traditional case ($MPK = (1-\alpha)z_t k_t^{-\alpha}$).

is a constant ratio representing the *steady-state* allocation of capital between domestic and productive aims.[26] It has be less than unity in order for k_t mainly behaving as factor input

Assumption 1 $\frac{\theta^*}{1-\theta^*} < 1$.

Moreover, g is positive only if the following condition holds

Assumption 2 $A > \delta + \rho$.

The device $\gamma + \lambda = \alpha$ leads the economy to behave as in the AK model. g depends on total spillover of consumption; ϵ is an average between the shares of *horizontal* allocation of the externality (ν and μ), weighted by those parameters which specify its *vertical* assignment (γ and λ).[27]
Aside from the inner propensity to hi-tech items $(1-\psi)$, it has to be stressed that g is positively correlated with c_0/y_0, that is the initial share of resources devoted to traditional goods.
At the beginning of this technological age that makes hi-tech goods available for consumption, it is clear that the more basic needs are satisfied (c_0/y_0 is high), the more people acquire knowledge based goods to meet other necessities. In this way the economy has a higher accumulation rate so to benefit from a larger spillover.

The present model is evidently unfit to explain the long-run growth as it considers learning-by-doing as the unique engine for development.
It misses to take into account the effective forces and real incentives stimulating innovation.[28] The existing trade-off between the size of spillover and marginal productivity of capital makes the matter clear ($\frac{\partial g}{\partial \alpha} < 0$).

[26] $\frac{\theta^*}{1-\theta^*}$ can be easily obtained dividing (8) by (9). After some algebra we have $\frac{\theta^*}{1-\theta^*} = \frac{1-\psi}{\psi}\frac{c_t/y_t}{1-\alpha}$; here, c_t/y_t can be replaced by the ratio of initial values c_0/y_0, because these variables grow at the same *steady-state* rate (g).
It must be stressed that c_0/y_0 is *constant* but *not exogenous*: both c_0 and y_0 stems from the initial value k_0 (the exogenous parameter).

[27] Since households do not consider capital spillover, a benevolent planner's intervention is required to avoid a BGP featured by under-accumulation (less hi-tech consumption and investment than the social optimum). For the centralized problem see Venturini (2003).
As Boucekkine *et al.* (1999) point out, the planner correctly measures the spillover of k_t on q_t, making it higher than in the decentralized economy. Such efficiency index dictates the obsolescence speed and, as a result, in the centralized framework there is a negative externality that partially offsets the positive spillover.

[28] Krusell (1998) and Ortigueira (2003) respectively consider R&D activities and human capital as endogenous forces for development in frameworks dealing with embodiment.
Grossman and Helpmann (1991) analyze the role of a loving-for-variety consumption within an economy featured by a R&D sector. The increasing number of varieties leads R&D unit cost to decrease. See also Barro and Sala-I-Martin (1995).

3.4 The Productivity Resurgence: the New Economy Age (1995-2001)

The productivity puzzle (1973-95) seemed to suggest that ICT were accelerating more the obsolescence of economists' tools than the one of old capital vintages.
Skeptics argued that New Technologies were unable to foster growth by their own nature.
More realistically, the sluggishness of productivity was attributed to the small weight of Information Technology on capital stock.[29]
Furthermore, ICT required complementary changes in business organization and workforce skills so that a long time needed to find out evidence of their potential.
In addition, there was a statistical issue: the measurement techniques did not seem able to accurately gauge the rising output of services and the vertiginous quality improvement of some goods (for example, chips and computer).

Boucekkine *et al.* (2003) model the advent of Information Technology as a shock fostering the embodiment process: it provoked a reassignment of the learning externality from consumption to investment.
Since the Seventies the *acceleration* in the drop of investment price encouraged the dissemination of New Technologies among firms. Deflation went hand in hand with a *downward trend* in output per hour and TFP due to the faster obsolescence (see sect. 3.1).

In the mid-Nineties the United States sheered, switching to a new productivity regime.
The core of the resurgence was the semiconductors market: a fiercer competition and substantial innovative efforts gave rise to a marked efficiency gain and a further acceleration in price decline.[30]
A more intensive use of chips as intermediate inputs (more embodiment, $\Delta\lambda > 0$) has brought a deeper penetration of more powerful and cheaper hi-tech goods into the economy.
In the post-oil crises period only firms significatively adopted of Information Technology while since 1995 New Technologies have been also entering households' daily routine (figure 2).[31]

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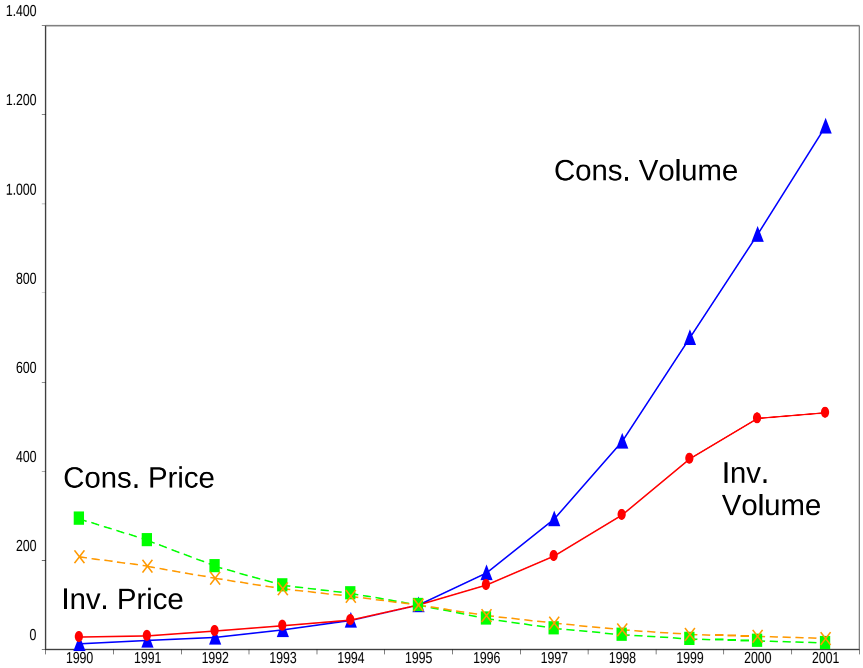
[29]See Oliner and Sichel (1994) for a discussion on the reasons of productivity slowdown.

[30]See section 1. According to many chief executives of semiconductors firms the increase in the innovative effort happened when the Asian markets collapsed (Oliner and Sichel (2000)), that is a bit later than estimated by Jorgenson (2001).

[31]Even if fig.2 is not instructive for a comparison on levels, it is very informative on real growth of IT investment and consumption. In nominal terms, NIPA data reveal that firms' purchases of computers were double than households' ones, accounting in average

Figure 2: **U.S. Consumption and Investment Expenditure on Computer (1990-2001): price and volume indexes (1995=100)**



Source: NIPA; U.S. Bureau of Economic Analysis.

From then on, the stock of hi-tech assets of the economy is likely to have reached a such size to engender a technological spillover able to speed up the development.

If IT shock of the mid-Nineties is interpreted as a further increase in the *embodiment* process ($\Delta\lambda > 0$), then the present framework is able to fit the U.S. story of last decade under the following conditions:

A) $\frac{\theta^*}{1-\theta^*} < e^{-\frac{1}{1-\lambda}}$,

B) $\nu - \mu > \varpi, \quad 0 < \varpi < 1$ and $\quad \varpi = \frac{1}{(1-\lambda)[-\ln(\frac{\theta^*}{1-\theta^*})]} \frac{A-\delta-\rho}{A}$.[32]

The share of consumer durables has to be *low* relatively to equipment (Cond. A) and, in addition, the consumption spillover *mainly* impact on TFP ($\nu - \mu$ has to reach the minimum level ϖ; cond. B).[33]

for one percent of GDP between 1995 and 2001.

[32]The former (A) is necessary, guaranteeing ϖ is less than unity. The latter (B) is sufficient when the other holds.

[33]Given the dual nature of the externality ($\nu - \mu > \varpi \quad \Rightarrow \quad (1-\mu) - (1-\nu) > \varpi$),

If both conditions are fulfilled, the quality improvement (and the resulting acceleration in price decline) of IT goods ($\frac{\partial g_q}{\partial \lambda} = -\frac{\partial g_p}{\partial \lambda} > 0$) leads labor and total factory productivity to change gear ($\frac{\partial g}{\partial \lambda} > 0$ and $\frac{\partial g_z}{\partial \lambda} > 0$).[34]
Finally, it is evident that cond. A and B also allow households' welfare

$$\Delta u(c_t, \theta k_t) = \psi g + (1-\psi) g_k$$

to improve:

$$\frac{\Delta u}{\Delta \lambda} = \psi \frac{\partial g}{\partial \lambda} + (1-\psi) \frac{\lambda}{1-\lambda} \frac{\partial g}{\partial \lambda} + \frac{1-\psi}{(1-\lambda)^2} g > 0.$$

3.5 Multi-sector Economy, Industrial Dynamics and Aggregate Growth (***two-final-sector model***)

The *productivity slowdown* and *resurgence* experienced by the U.S. have been so far told as an aggregate framework story.
No reference has been given on the drawbacks of the one-sector model that, actually, has gone under attack.
Ho and Stiroh (2001) argue that the framework originating from Solow (1960) is not able to explain the declining trend in relative prices. Given their perfect substitutability, competition leads the price of investment and consumption goods (in physical units) to be identical. This the reason why GHK (1997) are *forced* to introduce a quality index and deal with *effective* units of investment.

According to Whelan (2003) a multi-sector framework is better to represent the U.S. postwar performance, characterized by *constant* but *different* real growth rates of goods (durables *vs.* non-durables). These features cannot be met by the one-sector model.
Moreover, in discussing on (and rejecting) the multi-sector representation of the economy, GHK (1997) propose a way to aggregate output ($y_t = y_{1,t} + \frac{y_{2,t}}{q_t}$)

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cond. B can be also interpreted as requiring that the externality of productive capital affects much more on the efficiency of investment than consumption goods production.

[34]Cond. A and B are necessary and sufficient to have $\partial g_z / \partial \lambda > 0$, but are more binding than the ones guaranteeing $\partial g / \partial \lambda > 0$:

$$\frac{\partial g_z}{\partial \lambda} = -\frac{1-\alpha}{(1-\lambda)^2} g + \frac{\alpha - \lambda}{1-\lambda} \frac{\partial g}{\partial \lambda} \quad \Rightarrow \quad \frac{\partial g_z}{\partial \lambda} > 0 \quad \Leftrightarrow \quad \frac{\partial g_z}{\partial \lambda} > \frac{1-\alpha}{1-\lambda} \frac{g}{\gamma}.$$

Moreover, it is evident that cond. A and B also imply that $g_q = \Delta \frac{\dot{q}_t}{q_t} = -\Delta \frac{\dot{p}_t}{p_t} > 0$:

$$\frac{\partial g_q}{\partial \lambda} = \frac{1}{(1-\lambda)^2} g + \frac{\lambda}{1-\lambda} \frac{\partial g}{\partial \lambda}.$$

at odds with new techniques adopted by National Accounts (Whelan (2003), p.651).[35]
Finally, Oulton (2004) shows that GHK's framework, based on an *implicit* investment sector, consists in a particular case of the *two-final-sector* economy described by Whelan (2003).[36]

In order to make theory as close as possible to data, Whelan, *op. cit*, considers the economy as consisting in two final industries and the overall growth rate is obtained by aggregating sectoral outputs by chained weights (Tornqvist's index):

$$\frac{\dot{y}_t}{y_t} = \bar{\omega}_{1,t}\frac{\dot{y}_{1,t}}{y_{1,t}} + \bar{\omega}_{2,t}\frac{\dot{y}_{2,t}}{y_{2,t}}.$$

$\frac{\dot{y}_t}{y_t}$ uses as weights a two-year mean of the nominal share of outputs on aggregate income.[37]
As it will be clear later, this aggregation criterium avoids the isomorphism of a two-sector model when industry technology parameters are supposed identical.
As the capital-labor ratio is equal everywhere, when total income is a not- (or base-year) weighted sum of sectoral outputs, then the two-sector model collapses into one featured (and equally well described) by a single final industry (Greenwood *et al.* (1997), p. 357).

A two-sector economy perfectly fits that dichotomy between ICT-producing and -using industries usually taken into account by the empirical studies on ICT and economic performance.
Information Technology was not considered as primary source of growth until its impact on productivity was limited to few sectors (IT and few other durables; see Gordon (2000)).
More recently, a strong evidence has been found on pervasiveness of New Technologies. Stiroh (2002b), for example, points out that the 0.79% acceleration in GDP per hour between 1987-95 and 1995-2000 can be totally attributed to IT-producing and -using industries (respectively 0.17 and 0.83%).[38] Similar findings are reported by Nordhaus (2002).

[35]Whelan, *op. cit.*, points out that the multi-sector model of Greenwood *et al.* (1997) could be at most suitable to represent the U.S. economy before NIPA replaced base-year with chained-weights aggregation.

[36]In addition, the neoclassic economists argue that deflating all output by non-durable consumption price index, as GHK do, is rather anomalous for growth accounting. On the contrary, Pakko (2002), p.8, argues that it is the only technique to avoid that a fraction of investment-specific technical change is attributed to TFP.

[37]The chained-weights aggregation avoids the *substitution bias* of fixed-year indexes (as Laspeyres): the further back in time the base-year, the higher the growth rate as too high weights are attributed to those goods featured by a marked decline in prices.

[38]A negative contribution provided by those sectors that do not intensively use IT

In the following, we analyze the growth-enhancing role of hi-tech consumption in a two-final-sector economy where the durables industry is the only one taking advantage from the technological spillover.
This hypothesis meets the belief shared in the *embodiment controversy* that development is depending on the increasing efficiency of equipment.
The analysis will be displayed in two stages. At first, both neutral and incorporated technological change are taken into consideration and the *information shock* interpreted as a factor triggering embodiment.
In this case, only the hi-tech output ($y_{2,t}$) has quality improved (by $q_{e,t}$ and $q_{c,t}$) once it is accumulated into equipment ($k_{e,t}$) and consumer durables (d_t; $k_{s,t}$ are structures).

$$\begin{gathered} y_{1,t} = z_{1,t} k_{1s,t}^{\alpha_s} k_{1e,t}^{\alpha_e} l_{1,t}^{1-\alpha_s-\alpha_e}, \qquad y_{1,t} = c_{1,t} + i_{s,t} \\ y_{2,t} = z_{2,t} k_{2s,t}^{\beta_s} k_{2e,t}^{\beta_e} l_{2,t}^{1-\beta_s-\beta_e}, \qquad y_{2t} = c_{2,t} + i_{e,t} \\ \dot{k}_{s,t} = (1-\delta_s) k_{s,t} + i_{s,t}, \quad k_{s,t} = k_{1s,t} + k_{2s,t} \\ \dot{k}_{e,t} = (1-\delta_e) k_{e,t} + q_{e,t} i_{e,t}, \quad k_{e,t} = k_{1e,t} + k_{2e,t} \\ \dot{d}_t = (1-\delta_d) d_t + q_{c,t} c_{2,t}, \\ u(t) = u(c_{1,t}, d_t).^{39} \end{gathered} \tag{14}$$

In the second step, the investment-specific nature of progress is abandoned ($q_{e,t} = 1$ e $q_{c,t} = 1$); technology is only regarded as Hicks-neutral and $z_{2,t}$ picks up the entire spillover.
The resulting pure neoclassic framework[40] reflects the interpretation provided by Jorgenson (1966) on Solow (1960) when applied to a multi-sector economy.[41]

At this point, the reader is likely to question why not to skip the first step, passing directly from the one-sector economy featured by both kinds of progress (*disembodied* and *embodied*; see sect. 3.3) to a multi-sector setting only based on a Hicks-neutral technology.
The answer is that, neglecting the intermediate inputs market (basically chips) where the technological shock took place, hi-tech producers ($y_{2,t}$) have

capital.

[39]This framework neglects intermediate inputs.
See Oliner and Sichel (2002) for a model featured by the presence of intermediate inputs (semiconductors).

[40]Neoclassic in terms of representation of the economy without embodied progress.

[41]"...In a two-sector model Solow's assumption would be equivalent to the assumption that all technical change is of the disembodied variety but technical change is confined to the investment-goods sectors..." Jorgenson, *op. cit.*, p.10.

actually undergone an (exogenous) embodiment process. They take advantage from the innovations in semiconductors technology only when investing in new vintages of capital goods that *more deeply* incorporate *new* chips.

3.5.1 The Embodiment process in the multi-sectoral economy

In this industrial economy we suppose equal technology parameters among sectors ($\alpha = \beta$).[42]
Moreover, in order to facilitate the comparison with the one-sector framework of previous section, we hypothesize that traditional output is only consumed ($c_{1,t} = y_{1,t}$). As a result, there is only one kind of capital (equipment now simply indicated by k_t) that is proportionally allocated to traditional and hi-tech production by $1 - \theta_t$ and θ_t.
Once normalized to one the exogenous labor supply ($L = l_{1,t} + l_{2,t} = 1$), l_t and $1 - l_t$ represent the relative amount of variable input used in each industry.
Finally, we introduce two further hypotheses on (14): first, $\delta_e = \delta_d$ to guarantee an identical intensity in the use of durables at home and on the workplace (hereafter δ). Second, $q_{e,t} = q_{c,t}$ that implies a quality improvement of consumer durables as fast as for equipment (now simply q_t).[43]
These hypotheses yield the following framework:

$$
\begin{aligned}
c_{1,t} = y_{1t} &= z_{1,t}[(1-\theta_t)k_t]^{1-\alpha} l_t^{\alpha}, \\
c_{2,t} + i_t = y_{2,t} &= z_{2,t}(\theta_t k_t)^{1-\alpha}(1-l_t)^{\alpha}, \qquad (15) \\
\dot{k}_t &= q_t i_t - \delta k_t, \\
\dot{d}_t &= q_t c_{2,t} - \delta d_t, \\
u(c_{1,t}, d_t) &= \psi \log c_t + (1-\psi) \log d_t.
\end{aligned}
$$

[42]As it will be explained later, this hypothesis is fundamental to make the aggregate growth rate steady.

[43]$\delta_e = \delta_d$ (identical *wear and tear* at home and on the workplace) is a little more unrealistic than $q_{e,t} = q_{c,t}$: the former implies an utility optimization of consumers as intensive as the profit-seeking behavior of firms.
Nevertheless, for computer, this is a reasonable hypothesis (see Jorgenson and Stiroh (2000), table B1).
Furthermore, it has to be pointed out that tax regime may speed up the retirement so to induce firms to hold equipment for less time than households. However, this aspect cannot be taken into consideration when the permanent inventory method and geometric depreciation are jointly adopted.

Now relative prices (p_t) depend on competitiveness of markets. By the dual approach, it can be easily shown that p_t is the ratio of sector-specific TFPs:

$$p_t = \frac{p_{2,t}}{p_{1,t}} = \frac{z_{1,t}}{z_{2,t}} \quad \Rightarrow \quad \frac{\dot{p}_t}{p_t} = -\frac{\dot{z}_{2,t}}{z_{2,t}};^{44}$$

the second expression derives from the normalization of $z_{1,t}$ to 1.
Hi-tech industry presents the main features attributed to the only one sector of section 3.3:

$$z_{2,t} = z_2 f_z(d_t, k_t) = z_2(d_t^{\nu} k_t^{1-\nu})^{\gamma},$$
$$q_t = q f_q(d_t, k_t) = q(d_t^{\mu} k_t^{1-\mu})^{\lambda}.$$

Both indexes of efficiency (neutral and incorporated) depend on the economy-wide stock of durables and equipment. In steady-state, the technological externality is fully enjoyed by high-tech sector ($\alpha = \gamma + \lambda$).[45]
The Hamiltonian function of this intertemporal optimization problem is

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

The first-order maximum conditions with respect to control (θ_t, $c_{2,t}$ and l_t) and state variables (k_t and d_t) are:

$$\frac{\partial H(.)}{\partial \theta_t} = 0 \quad \Rightarrow \quad \frac{\psi}{1-\theta_t} e^{-\rho t} = \phi_{1,t} q_t \frac{y_{2,t}}{\theta_t}, \tag{16}$$

$$\frac{\partial H(.)}{\partial c_{2,t}} = 0 \quad \Rightarrow \quad \phi_{1,t} = \phi_{2,t}, \tag{17}$$

$$\frac{\partial H(.)}{\partial l_t} = 0 \quad \Rightarrow \quad \frac{\psi}{l_t} e^{-\rho t} = \phi_{1,t} q_t \frac{y_{2,t}}{1-l_t}, \tag{18}$$

$$\frac{\partial H(.)}{\partial k_t} = -\dot{\phi}_{1,t} \quad \Rightarrow \quad -\dot{\phi}_{1,t} = (1-\alpha)\frac{\psi}{k_t} e^{-\rho t} + \phi_{1,t}\big((1-\alpha) q_t \frac{y_{2,t}}{k_t} - \delta\big), \tag{19}$$

[44] $C_{i,t} = \frac{y_{i,t}}{z_{i,t}} \left(\frac{w}{\alpha}\right)^{\alpha} \left(\frac{R}{1-\alpha}\right)^{1-\alpha}$ is the unity cost of producing $y_{i,t}$; w and R are the steady-state remuneration of labour and capital (the jorgensonian rental price). In perfectly competitive markets price equals marginal cost $\left(p_{i,t} = \frac{\partial C_i}{\partial y_{i,t}}\right)$ and the expression for relative price p_t easily follows.

[45] This way to model ICT spillover fits well the results obtained by some econometric studies (see Stiroh (2002a)) that find little evidence of *non pecuniary externalities* outside the hi-tech industries.
Nevertheless, there is no consensus on this issue. For example, O'Mahony and Vecchi (2004) present a positive evidence for the United States. In addition, by an analysis on inter-industry transactions, Mun and Nadiri (2002) *measure* the importance of such spillover, once assumed that a sector benefits from trading with customers and suppliers well-endowed with IT assets.

$$\frac{\partial H(.)}{\partial d_t} = -\dot{\phi}_{2,t} \quad \Rightarrow \quad -\dot{\phi}_{2,t} = \frac{1-\psi}{d_t} e^{-\rho t} - \phi_{2,t}\delta; \tag{20}$$

$k_0 > d_0 > 0$[46] are the initial values of stock variables,

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

the two transversality conditions.
Dividing (18) by (16) it can be seen that each sector exploits factors in the same proportions ($\theta_t = 1 - l_t$).
In this framework, on the *Balanced Growth Path*,[47] the set of variables $\{c_{1,t}, c_{2,t}, y_{1,t},\ y_{2,t}, k_t, d_t, z_{2,t}, q_t\}$ grows at constant but different rates and inputs shares $\{\theta_t, l_t\}$ are time invariant (hereinafter θ and l).
In *steady-state* the traditional production function yields $g_1 = (1-\alpha)\frac{\dot{k}_t}{k_t}$ and the two accumulation laws $\frac{\dot{d}_t}{d_t} = \frac{\dot{k}_t}{k_t}$, once the equilibrium condition $\frac{\dot{c}_{2,t}}{c_{2,t}} = \frac{\dot{i}_t}{i_t}$ has been exploited.
The identity between the growth rate of state variables leads to a smart expression for the efficiency indexes $g_q = \lambda\frac{\dot{k}_t}{k_t}$ and $g_{z2} = (\alpha - \lambda)\frac{\dot{k}_t}{k_t}$ and, then, for hi-tech output $g_2 = (1-\lambda)\frac{\dot{k}_t}{k_t}$.
This result is fundamental because now every variable can be expressed as dependent on g_2:

$$g_1 = \frac{1-\alpha}{1-\lambda} g_2, \qquad g_k = g_d = \frac{1}{1-\lambda} g_2,$$

$$g_q = \frac{\lambda}{1-\lambda} g_2, \qquad g_{z2} = \frac{\alpha-\lambda}{1-\lambda} g_2.$$

As a consequence, in order to determine the equilibrium conditions of the economy, it only needs to compute the output growth rate of the sector 2. In this respect, g_q has to be substituted into the time log-derivative of (16):

$$g_2 = (1-\lambda)\Big(-\frac{\dot{\phi}_{1,t}}{\phi_{1,t}} - \rho\Big). \tag{21}$$

$-\frac{\dot{\phi}_{1,t}}{\phi_{1,t}}$ can be obtained similarly to the one-sector framework, by replacing the expression for $\phi_{1,t}$ from (16) into (19), once the latter equation has been divided by $\phi_{1,t}$ itself:

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

[46]This inequality guarantees k_0 to be the primary source of growth, corresponding to the Assumption 1 of one-sector model.

[47]As Whelan, *op. cit.*, points out, it would be more accurate to simply refer to as *steady-state* growth path, given the *different* growth rates of sectors.

The previous result exploits the condition $\theta = 1 - l$.
Replacing q_t and $z_{2,t}$ and the expression for $\frac{\dot{\phi}_{1,t}}{\phi_{1,t}}$ into (21) yields

$$g_2 = (1-\lambda)\big((1-\alpha)qz_2(d_0/k_0)^{\epsilon} - \delta - \rho\big), \qquad \epsilon = \gamma\nu + \lambda\mu. \tag{22}$$

This rate is stable because of the constancy of d_0/k_0 and positive when

Assumption 3 $\quad (1-\alpha)qz_2\big(d_0/k_0\big)^{\epsilon} > \delta + \rho.$

The *aggregate* growth rates of output (g) and TFP (g_z) are computed by adopting respectively Tornqvist's number index formula and Domar's criterium.
According to Domar (1961),[48] a synthetical index of the overall efficiency (Multi-Factor Productivity) can be obtained by weighting industry-specific TFPs with the nominal ratio between the sectoral gross output and GDP.
In this framework there are no intermediate inputs so that gross output equals value added. As a result, Domar's weights coincide with Tornqvist's ones for output. It yields:

$$g_y = \bar{\omega}_1 g_1 + \bar{\omega}_2 g_2, \qquad g_z = \bar{\omega}_1 g_{z1} + \bar{\omega}_2 g_{z2}.$$

The identity of technology parameters among industries ($\alpha = \beta$) implies that the nominal ratio between outputs $\big(p_t \frac{y_{2t}}{y_{1t}}\big)$ is time-invariant;[49] this also leads to the constancy of the income shares ($\bar{\omega}_i = \frac{1}{2}(\omega_{i,t-1} + \omega_{i,t}) = \omega_i$, where $\omega_i = \frac{p_{i,t}y_{i,t}}{\sum_{i=1}^{2} p_{i,t}y_{i,t}}$ and $i = 1, 2$).
This is the main property of the multi-sectoral framework because, as Whelan (2003) points out, only the time invariancy of income shares makes the aggregate output (and MFP) *steady*.
If the share of faster growing sector (ω_2) was increasing, at a given time the traditional industry would disappear conflicting with the utility of consumers: households need both goods to survive.

The aggregates rates can be reworded taking into account the explicit expression for g_1 as dependent on g_2:

$$g_y = g_2\big(1 - \frac{\gamma}{1-\lambda}\omega_1\big) = g_2 - g_{z2}\omega_1, \tag{23}$$

$$g_z = (1-\omega_1)g_{z2} = (1-\omega_1)\frac{\gamma}{1-\lambda}g_2. \tag{24}$$

[48]This criterium was proposed by Domar (1961) and formally demonstrated by Hulten (1978).

[49]
$$\frac{\dot{p}_t}{p_t} + \frac{\dot{y}_{2t}}{y_{2t}} - \frac{\dot{y}_{1t}}{y_{1t}} = -\frac{\dot{z}_{2,t}}{z_{2,t}} + \frac{\dot{y}_{2t}}{y_{2t}} - \frac{\dot{y}_{1t}}{y_{1t}} = -\frac{\alpha-\lambda}{1-\lambda}g_2 + g_2 - \frac{1-\alpha}{1-\lambda}g_2 = 0.$$

As (23) shows, sector 2 *pulls* the overall development ($g_1 < g_y < g_2$): the smaller the traditional production (and consumption) (ω_1), the faster the aggregate growth (g_y).
Sector 1 expands *at the expenses* of hi-tech activity that is the only one benefiting from the technological externality and increasing returns to scale.
Inter-industrial dynamics is explained by movements on prices (*neoclassic pecuniary spillover*) as evident from the second expression for g_y in (23).
The increasing TFP-efficiency of hi-tech producers lowers relative prices ($g_{z2} = -g_p$) encouraging traditional firms to adopt cheaper and more innovative capital goods.
Hence, sector 2 has less resources to invest and opportunities for further technological advances diminish.
The propulsive role of hi-tech industry evidently emerges, whenever a technological shock rising the embodiment hits the economy ($\Delta\lambda > 0$ as in section 3.3).
Under the following conditions

C) $\frac{d_0}{k_0} < e^{-\frac{1}{1-\lambda}}$,

D) $\nu - \mu > \varpi'; \quad 0 < \varpi' < 1, \quad \varpi' = \frac{1}{(1-\lambda)[-\ln(\frac{d_0}{k_0})]}\left(\frac{A' - \delta - \rho}{A'}\right)$,

where $A' = (1-\alpha)qz_2(\frac{d_0}{k_0})^{\epsilon}$, the *information shock* materializing in a rise of quality improvement of durables ($\Delta g_q > 0$) leads to a simultaneous acceleration in g_2 and g_{z2}.
Then, the latter effect generates a decline in prices ($\Delta g_p < 0$) so to foster traditional production as well.
Since the income shares are shock invariant ($\frac{\partial\omega_i}{\partial\lambda} = 0$),[50] the aggregate indexes of output and MFP are unequivocally raised by $\Delta\lambda$ ($\Delta g_y > 0$ and $\Delta g_z > 0$).
At first, the *information shock* involves ICT-producers; then, it is transmitted to the user sector. Straightforwardly, it boosts the overall development.

3.5.2 A pure Neoclassic multi-sector economy

Jorgenson (1966) stresses that the quality index q_t is not indispensable in a multi-sector framework.

[50]This depends on the shock invariancy of $p_t \frac{y_{2t}}{y_{1t}}$:

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

The increasing efficiency of equipment can be picked up by a Hicks-neutral technology index growing faster in the investment industry than in any other sector.
This is the reason why the incorporated nature of progress is relaxed ($\lambda = 0 \quad \Rightarrow \gamma = \alpha;\ q = 1$) in the present section. Now, $z_{2,t}$ collects the entire spillover as the TFP of low-tech sector has been normalized to 1:

$$z_{2,t} = z_2\big(d_t^{\nu} k_t^{1-\nu}\big)^{\alpha} = z_2\big(\frac{d_t}{k_t}\big)^{\alpha\nu} k_t^{\alpha}.$$

In this neoclassic framework the optimization problem is much more simplified as

$$\frac{\dot{k_t}}{k_t} = \frac{\dot{d_t}}{d_t} = \frac{\dot{y_{2,t}}}{y_{2,t}} = g_2, \qquad \frac{\dot{p_t}}{p_t} = -\frac{\dot{z_{2,t}}}{z_{2,t}} = -\alpha\frac{\dot{k_t}}{k_t}.$$

These results easily lead to the growth rate of sector 2

$$g_2 = \big((1-\alpha)z_2\big(\frac{d_0}{k_0}\big)^{\alpha\nu} - \delta - \rho\big). \tag{25}$$

This is stable because of the exogenous ratio between state variables (d_0/k_0) and positive if the following condition is fulfilled

Assumption 4 $\quad (1-\alpha)z_2\big(d_0/k_0\big)^{\alpha\nu} > \delta + \rho.$

In essence, the restriction on the nature of technical change does not modify the aggregate indexes of output and efficiency

$$g_y = \omega_1 g_1 + \omega_2 g_2 = g_2\big(1 - \alpha\omega_1\big) = g_2 - g_{z2}\omega_1, \tag{26}$$

$$g_z = \omega_2 g_{z2} = (1-\omega_1)\alpha g_2. \tag{27}$$

Obviously, inter-sectoral dynamics is unchanged and hi-tech sector remains critical to grow.

The jorgensonian version of the multi-sector economy presented in this work nevertheless features for two drawbacks, both depending on the hypotheses introduced on (14).
First, since $z_{2,t}$ enjoys the entire spillover (of size α), the high-tech industry exactly behaves as described by Romer (1986): there is no more distinction between Hicks- or Harrod-neutral technology.
Second, the *information shock* can be interpreted neither as a factor increasing the embodiment nor as a raise in the size of the externality, given the trade-off between capital spillover and marginal productivity.[51]

[51] An increase in α reduces the output elasticity to capital and, consequently, the growth rate. See section 3.3.

Consequently, in this framework, the *information revolution* is considered as a shock putting in action an endogenous mechanism for development based on learning-by-doing ($z_{2,t}$) that replaces a *pre-existing* exogenous technical change (a deterministic trend, a_t):

$$y'_{2,t} = a_t f(k_t, l_t), \qquad a_t = a_0 e^{g_a t}, \qquad g_a > 0.$$

It can be easily shown that the massive dissemination of Information Technology boosts the growth rate when $a_t < z_{2,t}$; this inequality requires the following condition

E) $a_0 < z_0$.

z_0 collects every parameter resulting in $z_{2,t}$, once all endogenous variables (d_t and k_t) have been replaced

$$z_0 = z_2 d_0^{\alpha\nu} k_0^{\alpha(1-\nu)},$$

and the equality $g_a = \alpha g_2$ is taken into account.

If the condition on TFP holds (cond. E), then the technological shock gives rise to the macroeconomic scenario described in previous sections.

4 Concluding Remarks

This paper has taken into account the increasing importance of computers for the economic growth resulting from the IT price shock of the mid-1990s. If, as it is argued, ICT engender spillovers (here supposed *via* learning-by-doing), then hi-tech consumption may also emerge as source of growth, complementarily to investment.
In this respect, the present work shows that the strong recovery of the U.S. productivity in mid-Nineties may derive from the massive spread of computers both among *firms* and *households*.

The role of hi-tech consumption has been analyzed either in an aggregate (one-sector) or in a multi-sector (or two-sector) framework.
In the former both neutral and investment-specific progress have been taken into consideration in order to explain the rising efficiency of investment goods. The *information shock*, that gave rise to the so-called New Economy Age, is interpreted as an increase in the incorporated nature of technology.
In the latter, the analysis has been extended to a two-sector economy where the hi-tech industry is the only enjoying increasing returns. At first, the hypothesis on the co-existence between embodied and neutral progress has been maintained; then, it has been relaxed in order to study a pure neoclassic

economy.
In every framework analyzed, the model is able to fit (under certain conditions) the productivity performance experienced by the United States from the mid-Nineties onwards.

Even if no relevant contribution to the *embodiment controversy* (the debate on the link between progress and economic growth) emerges from the present work, it is worthwhile drawing a final consideration on this issue.
As this model takes the information shock as *given* (the intermediate inputs sector where it took place is neglected), then the distinction between embodied and disembodied technical change can be also maintained in the two-sector economy.
Only if a fully comprehensive multi-sector framework is adopted, featured by the relevant final and intermediate markets (or, as in sect. 3.5.2, the IT shock is supposed to generate an endogenous mechanism for growth -based on learning-by-doing- in place of a deterministic trend), then the embodied nature of technical change is no more strictly indispensable to model the rising efficiency of equipment and the recent development dynamics.

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