Technological shocks and IT revolutions*

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1 Introduction

The US economy has experienced a spectacular boom from 1995 to 2000, with a very rapid GDP growth (around 5% in 1999 for example), and markedly low inflation and unemployment rates (around 2 and 4 percent respectively). This exceptional expansion period has been attributed by many analysts to the rise of the communication and information technologies sector (IT). In particular, the huge gains in productivity registered in the computers sector (i.e., in the production of hardware) have been put forward as the main engine of the recent boom. While the growth rate of output per hour in the computers sector has averaged around 18% in the interval 1972-1995, it rises to more than 40% in average during the recent boom (see Gordon, 1999 and 2000). The same diagnosis has been provided by Jorgenson and Stiroh (1999) and Whelan (2000).

On a more theoretical ground, some economists have foreseen through this spectacular boom the emergence of a "New Economy", an information-based era involving some crucial organizational changes yielding evenly high productivity growth. Among other predictions of this enthusiastic view, the productivity slowdown is claimed to be over. Some important contributions deal explicitly with the latter topic, Greenwood and Yorukoglu's paper (1997) being representative. The story told puts forward a crucial stylized fact, namely the decline of the relative price of capital in the US economy,

* The financial support of the ARC program "Growth and Incentive Design" is gratefully acknowledged.
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especially after the first oil shock (see Gordon, 1990). This trend is interpreted as an evidence that technological progress is investment-specific, or embodied. There has been an acceleration in the rate of embodied technical progress since 1974, corresponding to the rise of the information technologies; however, the adoption of such innovative tools and methods is costly and requires specific human and physical capital to be efficiently enforced. Meanwhile labor and total factor productivity growth may slowdown. Once the adoption and adjustment costs paid, the economy will enter an age of the information technologies with further complementary innovations, and this productivity slowdown will be completely over. Though these theorists do not provide a detailed and specific analysis of the outcomes of the boom period 1995-2000 and its viability, their contributions are usually invoked by many analysts as a theoretical support to the emergence of an IT-based economy, a productivity enhancing "New Economy". There are several arguments and facts calling for more caution.

(i) It is not statistically clear that the IT sector's productivity gains have spread over the whole economy, argued Gordon (1999). According to this author, after correcting for the cycle, the productivity slowdown has even worsened in the durable, non-computers manufacturing sector. Though likely to be quantitatively inaccurate,[1] Gordon's argument calls for a serious appraisal of the potential spillovers of the IT sector, especially if one is primarily concerned with the long-run sustainability of an IT-driven growth regime.

(ii) Another point raised by Gordon (2000) but also by Jorgenson and Stiroh (1999) refers to the substitution effects of the IT boom. This boom period is indeed first characterized by a massive investment in IT equipment, in replacement of non-computers equipment. This is true for firms, and for households as well. This trend is favored by a continuous decline of the price of IT equipment (-17% on average for firms' IT purchases, and -24% for households' purchases over the period 1990-1996). According to Jorgenson and Stiroh (1999), this massive substitution does not necessarily means technological progress as this latter concept is understood by economists.

(iii) On a more theoretical ground, if one understands the current growth regime as principally driven by embodied technical progress, a rigorous analysis of its viability should account for the specific features of embodied technological progress. In particular, one has to account for the obsolescence costs linked to the latter, and for the limited channel through which it operates (namely, the new investment goods, around 7% of total capital stock in the US economy). If the IT-growth regime means more *embodiment* at the expense of disembodied technical change, this reassignment is not necessarily favorable to long-run growth, as pointed out by Boucekkine, del Rio and Licandro (1999).

[1] Indeed, the recent successive revisions of US NIPA undermine in a way the findings of all the NIPA based studies before 1999.

(iv) Last but not least, the latest performances of the US economy call for less euphoria and more caution, although the current recession may well be short-lived with valuable correction and "cleansing" mechanisms. More fundamental issues need to be tackled, and among them, the viability of the so-called e-commerce is a crucial and decisive question. The legal problems that the major start-ups are confronting (e.g. the Napster's trial) are certainly harmful for the development of Internet. Even the successful start-ups which are not involved in legal disputes are by now facing a very serious financial crisis (e.g. the case of Amazon.com). More generally there is a clear institutional problem still to be settled in order to build up a safe and efficient intellectual property rights system in the current information age.

Overall, more work is still to be done to understand more deeply the determinants, consequences, regulation and viability of the "New Economy". Some preliminary theoretical investigations are in particular most welcome, given the extreme complexity of the topic. This paper takes this approach. In particular, we aim at bringing out some preliminary lessons from the R&D- based endogenous growth theory. Indeed, one of the most important characteristics of IT companies is the intensity of their R&D effort (see the R&D policy of Intel for example in Segerstrom, 2000). We will use the simplest endogenous growth model built up to capture this effort, namely Romer's model (1990). Since the embodiment of technical advances in capital goods is a fundamental feature of IT sectors, we consider a Romer model with endogenous embodied technical progress. Previous contributions taking this approach are del Rio (1999) and Boucekkine and de la Croix (2001). We additionally borrow from the latter contribution the interpretation of the variables of the model in terms of hardware, software and efficient capital in such a way that we can distinguish between a positive supply shock in the production of efficient capital and a similar shock in the creation and/or production of new softwares. This distinction allows us to deliver the basic lessons that can be drawn from the endogenous growth theory as to the long term viability of IT booms.

Section 2 presents the four different sectors of activity (physical good, capital good, immaterial capital, research) and characterizes the equilibrium. Section 3 compares the transitory and permanent effects of productivity shocks taking place in the different sectors. This comparison is performed in a calibrated version of the model. Section 4 concludes.

2 The model

The model builds on Boucekkine and de la Croix (2001) and Romer (1990). It is a multisectoral model written in discrete time with endogenous growth and horizontal differentiation. In order to get a much clearer illustration of the sectoral substitution effects favorable to the IT sectors, we use much simpler specifications of the labor market and research activity compared with the latter contribution.[2]

2.1 The producer of physical goods

The final good sector produces a composite good that is used either to consume or to invest in physical capital. It uses efficient capital and labor. Efficient capital is built from physical capital and immaterial capital in the equipment sector. Let $K_{t,s}$ represent the efficient capital stock bought at time t (i.e., the vintage t) and still in use at time $s \geqslant t$. We assume that the depreciation rate, δ, is constant so

$$K_{t,s} = K_{t,t}(1-\delta)^{s-t} \tag{1}$$

At time $s \geqslant t$, the vintage t is operated by a certain amount of labor, say $L_{t,s}$. Let $Y_{t,s}$ be the output produced at time s with vintage t. Under a Cobb-Douglas technology *à la Solow* (1960), we have :

$$Y_{t,s} = z_s K_{t,s}^{\alpha} L_{t,s}^{1-\alpha} \tag{2}$$

with $\alpha \in [0,1]$. The variable z_s represents *disembodied* technological progress. The discounted profits of investing $K_{t,t}$ in vintage t are given by :

$$\Pi_t = \sum_{s=t}^{\infty} \left(Y_{t,s} - w_s L_{t,s}\right) R_t^s - d_t K_{t,t}, \tag{3}$$

where

$$R_t^t = 1 \text{ and } R_t^s = \prod_{\tau=t+1}^{s} \left(\frac{1}{1+r_\tau}\right)$$

is the discounted factor at time s and r_τ is the interest rate at time τ. w_s is the wage at time s. d_t is the price of efficient capital. The representative firm chooses efficient capital and the labor allocation across vintages in order to maximize its discounted profits taking prices as given and subject to its technological constraint. The first order conditions with respect to efficient capital and labor are respectively :

$$\alpha\, K_{t,t}^{\alpha-1} \sum_{s=t}^{\infty} R_t^s\; z_s\; (1-\delta)^{\alpha(s-t)}\; L_{t,s}^{1-\alpha} = d_t, \tag{4}$$

$\forall s \geqslant t$:

$$(1-\alpha)\; z_s K_{t,s}^{\alpha}\; L_{t,s}^{-\alpha} = w_s \tag{5}$$

[2] Boucekkine and de la Croix (2001) are very much concerned with the *productivity slowdown* and with the income inequality consequences of IT revolutions. We omit these aspects here.

Note that Equations (5) determine the labor allocation at time s to vintage t. Solow (1960) shows to aggregate these vintage equations. From (5), we get :

$$L_{s,t} = \left(\frac{(1-\alpha)\ z_t}{w_t} \right)^{\frac{1}{\alpha}} K_{s,t} \tag{6}$$

Defining aggregate variables as : $K_t = \sum_{s=-\infty}^{t} K_{s,t}$, $L_t = \sum_{s=-\infty}^{t} L_{s,t}$, $Y_t = \sum_{s=-\infty}^{t} Y_{s,t}$, it follows from (6) that :

$$L_t = \left(\frac{(1-\alpha)z_t}{w_t} \right)^{\frac{1}{\alpha}} K_t, \tag{7}$$

which implies after some simple algebraic operations that : $Y_t = z_t K_t^{\alpha} L_t^{1-\alpha}$.

2.2 The producer of efficient capital

This part of the model is identical to Boucekkine and de la Croix's specifications. The producer of efficient capital uses physical capital (or hardware) bought from the final good producers, and immaterial capital sold by the software producers. It builds efficient capital from these two inputs and sells it to the final good firm. Efficient capital $K_{t,t}$ is built following a constant return to scale technology :

$$K_{t,t} = e_t Q_t^{\lambda} I_t^{1-\lambda} \tag{8}$$

The parameter λ belongs to $(0,1)$. The productivity variable e_t will be used to model productivity shocks specific to the IT industry. The variable Q_t is the immaterial capital embodied in the vintage $K_{t,t}$. It is built from a series of intermediate goods as

$$Q_t = \left(\int_0^{n_t} x_{i,t}^{\frac{\sigma-1}{\sigma}} \mathrm{d}i \right)^{\frac{\sigma}{\sigma-1}} \tag{9}$$

n_t is the number of varieties available in t, $x_{i,t}$ is the quantity of input used in t of variety i and $\sigma > 1$ is the elasticity of substitution between two varieties. Profits at time t are :

$$d_t e_t \left(\int_0^{n_t} x_{i,t}^{\frac{\sigma-1}{\sigma}} \mathrm{d}i \right)^{\frac{\lambda\sigma}{\sigma-1}} I_t^{1-\lambda} - I_t - \int_0^{n_t} p_{i,t} x_{i,t} \mathrm{d}i$$

where d_t is the price of efficient capital and $p_{i,t}$ is the price of software of variety i. Denoting by $q_t = Q_t/I_t$ the software-hardware ratio, the first order conditions with respect to I_t and $x_{j,t}$ are :

$$(1-\lambda)e_t d_t q_t^{\lambda} = 1 \tag{10}$$

$\forall j \in [0, n_t]$:

$$\lambda e_t d_t q_t^{\lambda - 1} \left(\frac{Q_t}{x_{j,t}} \right)^{\frac{1}{\sigma}} = p_{j,t} \tag{11}$$

Using equations (10) and (11), we get :

$$\frac{x_{i,t}}{Q_t} = \left(\frac{\Phi}{q_t} \right)^{\sigma} p_{i,t}^{-\sigma}, \tag{12}$$

where $\Phi = \frac{\lambda}{1-\lambda}$.

2.3 The producer of immaterial capital

This section builds on Romer (1990). The production of any variety i of immaterial capital (or software) uses labor according to the following linear technology :

$$x_{i,t} = \gamma_t \, \widetilde{L}_{i,t}, \tag{13}$$

where γ_t is labor productivity in this sector. The producer behaves monopolistically and maximizes with respect to $x_{i,t}$ the static profit $\pi_{i,t} = p_{i,t} \; x_{i,t} - w_t \; \widetilde{L}_{i,t}$, given the demand for the variety i (12). The first order condition is

$$x_{i,t} = \left(\frac{\sigma - 1}{\sigma} \right)^{\sigma} Q_t \left(\frac{\Phi}{q_t} \right)^{\sigma} \left(\frac{\gamma_t}{w_t} \right)^{\sigma} \tag{14}$$

Substituting this equation into (12), one obtains the standard markup pricing formula and the subsequent optimal profit :

$$p_{i,t} = \left(\frac{\sigma}{\sigma - 1} \right) \frac{w_t}{\gamma_t}, \tag{15}$$

and

$$\pi_{i,t} = \left(\frac{w_t}{\gamma_t} \right)^{1-\sigma} \frac{1}{\sigma - 1} \left(\frac{\sigma - 1}{\sigma} \right)^{\sigma} Q_t \left(\frac{\Phi}{q_t} \right)^{\sigma} \tag{16}$$

2.4 The research activity

This section also builds on Romer (1990). Beside producing softwares, the immaterial capital sector expands their range. The increment of the total number of softwares depends on labor allocation to research $\overline{L}$, on the number of pre-exisiting varieties (Romer's externality) n_{t-1} and on a productivity variable μ_t :

$$n_t - n_{t-1} = \mu_t \overline{L}_t n_{t-1} \tag{17}$$

The cost of increasing the number of varieties by one unit is $\frac{w_t}{\mu_t n_{t-1}}$. The unit cost increases with the skilled wage and decreases with the level of productivity μ_t. There will be entry of new firms until this cost is equal to the discounted flow of profits linked to one invention. This equilibrium condition that determines the number of new firms n_t can be written : $\frac{w_t}{\mu_t n_{t-1}} = \sum_{s=t}^{\infty} R_{t,s}\pi_{i,s}$. Using (16), one can rewrite this condition as :

$$\frac{w_t}{\mu_t n_{t-1}} = \frac{1}{\sigma-1}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\sum_{s=t}^{\infty} R_{t,s}\left(\frac{w_s}{\gamma_s}\right)^{1-\sigma} Q_s\left(\frac{\Phi}{q_s}\right)^{\sigma},$$

or

$$\left(\frac{w_t}{\mu_t n_{t-1}} - \frac{w_{t+1}}{\mu_{t+1}n_t}\frac{1}{(r_{t+1}+1)}\right)(\sigma-1)^{1-\sigma}\sigma^{\sigma} = \left(\frac{w_t}{\gamma_t}\right)^{1-\sigma} q_t I_t\left(\frac{\Phi}{q_t}\right)^{\sigma} \tag{18}$$

2.5 Households and equilibrium

To close the model, we have to specify the representative household behaviour. We assume that she consumes, saves either and in physical capital or in the research activity, and supplies a fixed amount of labor (say L) inelastically. She maximizes the discounted sum of instantaneous utility :

$$\sum_{t=0}^{\infty}\rho^t \ln C_t$$

where ρ is the psychological discount factor and the utility function is logarithmic. The budget constraint is $A_{t+1} = (1+r_{t+1})A_t + w_t L - C_t$ where A_t stands for the assets detained by households. The first-order necessary condition for this problem is

$$\frac{C_{t+1}}{C_t} = (1+r_{t+1})\rho \tag{19}$$

which, together with the usual transversality condition, is sufficient for an optimum.

Finally the following market equilibrium relationships should hold. Equilibrium on the labor market implies that the labor force is employed either in the final good sector, in the intermediate good sector or in the research sector :

$$L = L_t + \int_0^{n_t}\tilde{L}_{i,t}\mathrm{d}i + \overline{L_t} \tag{20}$$

Equilibrium on the final good market implies

$$Y_t = C_t + I_t \tag{21}$$

2.6 Characterization of equilibrium paths

We are now able to characterize an equilibrium path. The following equations summarizing the first-order optimality conditions and market equilibrium relationships derived above.

Proposition 1. *Given the initial conditions K_{-1} and n_{-1}, an equilibrium is a path*

$$\{w_t, q_t, I_t, K_t, r_{t+1}, n_t, C_t\}_{t\geqslant 0}$$

that satisfies the following conditions:

$$\left(\frac{(1-\alpha)z_t}{w_t}\right)^{\frac{1}{\alpha}} K_t + n_t \gamma_t^{\sigma-1}\left(\frac{\sigma-1}{\sigma}\right)^{\sigma} q_t^{1-\sigma} I_t \left(\frac{\Phi}{w_t}\right)^{\sigma} + \frac{n_t - n_{t-1}}{\mu_t n_{t-1}} = 1 \quad (22)$$

$$z_t^{\frac{1}{\alpha}}\left(\frac{1-\alpha}{w_t}\right)^{\frac{1-\alpha}{\alpha}} K_t = C_t + I_t \quad (23)$$

$$\alpha(1-\lambda)e_t q_t^{\lambda} z_t^{\frac{1}{\alpha}}\left(\frac{1-\alpha}{w_t}\right)^{\frac{1-\alpha}{\alpha}} = 1 - \frac{e_t}{e_{t+1}}\left(\frac{q_t}{q_{t+1}}\right)^{\lambda}\frac{(1-\delta)}{(1+r_{t+1})} \quad (24)$$

$$\frac{C_{t+1}}{C_t} = (r_{t+1}+1)\rho \quad (25)$$

$$K_t = e_t q_t^{\lambda} I_t + (1-\delta)K_{t-1} \quad (26)$$

$$n_t^{\frac{1}{\sigma-1}}\left(\frac{\sigma-1}{\sigma}\right) = \frac{q_t w_t}{\gamma_t \Phi} \quad (27)$$

$$\left(\frac{w_t}{\mu_t n_{t-1}} - \frac{w_{t+1}}{\mu_{t+1} n_t}\frac{1}{(r_{t+1}+1)}\right)(\sigma-1)^{1-\sigma}\sigma^{\sigma} = \left(\frac{w_t}{\gamma_t}\right)^{1-\sigma} q_t I_t \left(\frac{\Phi}{q_t}\right)^{\sigma} \quad (28)$$

Equation (22) is the labor clearing condition where the expressions of labor demands in the production and invention of softwares are developed thanks to the production functions of both activities and using the demand function for varieties (12). Equation (23) is the final good market clearing condition rewritten using the aggregate production function of that good and the demand function (7). Equation (24) is a re-formulation of the optimality condition (4) with respect to efficient capital, using successively the labor demand function per vintage (6) and the optimality condition with respect to hardware in the efficient capital sector (10). Equation (26) gives the law of motion of the aggregate stock of efficient capital in our economy, it is derived from the definition of this aggregate variable, plus the production function in the efficient capital sector. $e_t q_t^{\lambda}$ can be seen as a measure of embodied technical change in line with Greenwood, Hercowitz and Krusell (1997). Contrary to these authors, the embodied technical change is endogenous in our model, as it is in Krusell (1998) and Boucekkine and de la Croix (2001). Equation (27) is just a re-formulation of the optimality condition (14) using the definition of the aggregate variable Q_t.

3 Calibration and simulations

3.1 Balanced growth paths

Along a balanced growth path (BGP), we assume that the exogenous productivity variables z_t, e_t, γ_t and μ_t are constant. Each endogenous variable grows at a constant rate. Call g_x the growth factor of a variable x and $\bar{x}$ its level along a BGP : $x_t = \bar{x} g_x^t$. It is trivial to prove that the model implies the following growth restrictions :

$$g_Y = g_w = g_C = g_I = g_q^{\frac{\lambda\alpha}{1-\alpha}} \tag{29}$$

$$g_K = g_q^{\frac{\lambda}{1-\alpha}} \tag{29}$$

$$g_n = g_q^{(\sigma-1)\frac{(\lambda\alpha+1-\alpha)}{1-\alpha}} \tag{29}$$

Note that the stock of capital grows faster as it includes improvements in the embodied productivity. To determine g_q, we need an additional information, which is provided by the restrictions on the long-run levels. Computing these restrictions from the dynamic system (22)-(28) we end with 7 equations for 8 unknowns ($\bar{w}$, $\bar{n}$, $\bar{q}$, $\bar{I}$, $\bar{C}$, $\bar{K}$, $\bar{r}$ and g_q) since all the other growth rates can be expressed in terms of g_q. The system in terms of levels is therefore undetermined, which is a usual property of endogenous growth models. Fortunately, it is always possible to rewrite this system in such way that we get rid of this indeterminacy. As usual, this is done by using deflated variables. Indeed, the dynamic system (22)-(28) can be rewritten as a function of 7 stationary variables, which are : $\widehat{C}_t = \frac{C_t}{w_t}$, $\widehat{I}_t = \frac{I_t}{w_t}$, $\widehat{q}_t = \frac{q_t}{w_t^{\omega_1}}$, $\widehat{n}_t = \frac{n_t}{w_t^{\omega_2}}$, $\widehat{K}_t = \frac{K_t}{w_t^{\omega_3}}$, $g_t = \frac{n_t}{n_{t-1}}$, where $\omega_1 = \frac{1-\alpha}{\lambda\alpha}$, $\omega_2 = \frac{(\sigma-1)(\lambda\alpha+1-\alpha)}{\lambda\alpha}$ and $\omega_3 = \frac{\lambda}{(\sigma-1)(\lambda\alpha+1-\alpha)}$. The stationarized system is :

$$((1-\alpha)z_t)^{\frac{1}{\alpha}} \widehat{K}_t \widehat{n}_t^{\omega_3} + \widehat{n}_t \gamma_t^{\sigma-1} \left(\frac{\sigma-1}{\sigma}\right)^{\sigma} \widehat{q}_t^{1-\sigma} \widehat{I}_t \Phi^{\sigma} + \frac{g_t - 1}{\mu_t} = 1$$

$$z_t^{\frac{1}{\alpha}} (1-\alpha)^{\frac{1-\alpha}{\alpha}} \widehat{K}_t \widehat{n}_t^{\omega_3} = \widehat{C}_t + \widehat{I}_t$$

$$\alpha(1-\lambda) z_t^{\frac{1}{\alpha}} (1-\alpha)^{\frac{1-\alpha}{\alpha}} e_t \widehat{q}_t^{\lambda} = 1 - \frac{e_t}{e_{t+1}} \left(\frac{\widehat{q}_t}{\widehat{q}_{t+1}}\right)^{\lambda} \left(\frac{\widehat{n}_t}{\widehat{n}_{t+1}} g_{t+1}\right)^{-\lambda\frac{\omega_1}{\omega_2}} \frac{(1-\delta)}{(1+r_{t+1})}$$

$$\frac{\widehat{C}_{t+1}}{\widehat{C}_t} \left(\frac{\widehat{n}_t}{\widehat{n}_{t+1}} g_{t+1}\right)^{\frac{1}{\omega_2}} = (r_{t+1}+1)\rho$$

$$\widehat{K}_t - (1-\delta)\widehat{K}_{t-1} g_t^{-\omega_3} = e_t \widehat{q}_t^{\lambda} \widehat{I}_t \widehat{n}_t^{-\omega_3}$$

$$\widehat{n}_t^{\frac{1}{\sigma-1}} \left(\frac{\sigma-1}{\sigma}\right) = \frac{\widehat{q}_t}{\gamma_t \Phi}$$

$$\frac{(\sigma-1)^{1-\sigma}\sigma^{\sigma}\gamma_t^{1-\sigma}}{\Phi^{\sigma}} \left(\frac{g_t}{\mu_t} - \frac{1}{\mu_{t+1}(r_{t+1}+1)} \left(\frac{\widehat{n}_t}{\widehat{n}_{t+1}} g_{t+1}\right)^{\frac{1}{\omega_2}}\right) = \widehat{n}_t \widehat{q}_t^{1-\sigma} \widehat{I}_t$$

Table 1 : *Parameters' values*

Parameter	symbol	value
Labor supply	L	1
Total factor productivity in the final sector	z	1
Rate of depreciation of capital	δ	0.04
Psychological discount factor	ρ	0.97
Elasticity of substitution between varieties of softwares	σ	2
Labor share in the final sector	a	0.7
Total factor productivity in the research sector	μ	1.2
Total factor productivity in the efficient capital sector	e	6
Unskilled labor productivity in the intermediate sector	γ	0.2
Share of software in the production of efficient capital	λ	0.5

The stationarized system has now 7 equations with 7 variables. Unfortunately, this system is analytically so complicated either in the short run or along a BGP that no accurate analytical characterization is allowed. So we will rely on a numerical approach.[3]

3.2 Calibration

Consider the following calibration of the model on the US economy, assuming that one model period of time is one year. A first set of parameters is fixed a priori to what we view as reasonable values given the empirical evidence available. The total factor productivity parameterized z is normalized to 1. The rate of depreciation of physical capital is 4% and the psychological discount factor is 0.97. We select the elasticity of substitution between varieties of softwares to obtain a mark-up rate of 2.

A second set of parameters is fixed in order to match a series of moments of the steady state we consider. The total factor productivity in the research sector μ is set to 1.2 in order to obtain a growth rate of the number of patents of 5% a year. Indeed there was 60000 new patents in 1983 and 110000 in 1997, which corresponds to an annual growth rate of 5%. The productivity parameter in the production of efficient capital e is fixed at 6 to have a ratio of capital to output of 3. The two remaining parameters, λ and γ, are used to calibrate the size of the new economy. The labor productivity in the intermediate sector and the share of softwares in the production of

3 All the simulations are performed using DYNARE, the package written by Juillard (1996).

efficient capital are such that the share of workers in the intermediate and research sectors is about 10%. This yields $\lambda = 1/2$ and $\gamma = 0.2$.

As stated above, we have calibrated the model to have a growth rate of the number of patents of 5%; this leads to a growth rate of output of 0.88% per year, which may be interpreted as the part of actual output growth generated by embodied technical progress. This is reasonable in the light of the empirical accounting debate on the measurement of growth rate under embodiment.[4] The interest rate is 4%. The share of investment in physical capital over output is 10.6%, which is also close to actual numbers.[5]

3.3 Technological shocks and IT revolutions

We consider three types of productivity shocks in the high-tech sectors of our economy : a shock on R&D productivity, μ_t, a shock on γ_t, the productivity in softwares' production, and a shock on e_t the productivity in the efficient capital sector. All the shocks are permanent from $t = 0$, non-anticipated and have a 1% intensity. The results are reported in Figure 1 to 3 where all the variables are expressed in levels. The following lessons can be brought out.

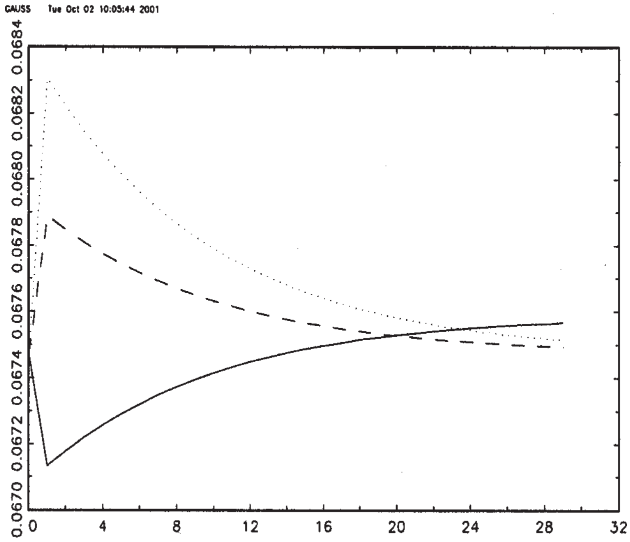
(i) **Labor allocation and IT booms** : In the three cases, the shocks give rise to a reallocation of labor favorable either to the R&D sector or the production of softwares or to both (Figures 1 and 2). This is at the basis of the registered IT booms. However, the economic mechanisms involved in each case are quite different. If labor productivity in research rises, more labor will be allocated to this activity, which pushes up the growth rate (Figure 3) of the number of softwares and launches the IT boom inducing higher growth rates of output and massive capital deepening at least in the short run. The shocks on e_t and γ_t yield also the same outcomes although with a different intensity and persistence. That is because the effect on labor allocation to R&D is different, being much less direct. A rise in e_t increases the profitability of producing efficient capital and increases the demand for inputs, notably for softwares. This in turn increases labor allocation to softwares' production and creation. An analogous story occurs when the productivity in the software sector goes up. In contrast, when a permanent improvement of research productivity occurs, the labor allocation need not be favorable to the sector producing softwares in the short run (see Figure 1). In such a case, the short term IT boom relies only on labor assignment to R&D.

(ii) **On the persistence of IT booms** : It should be first noted that the productivity shock on the R&D sector is the unique case in which a per-

[4] (1997) found that 63% of the US growth rate in the period 1954-1990 is due to embodied technical change. Given that the average annual growth rate over this period is around 1.24%, the contribution of embodiment into this figure amounts to 0.8% approximately.

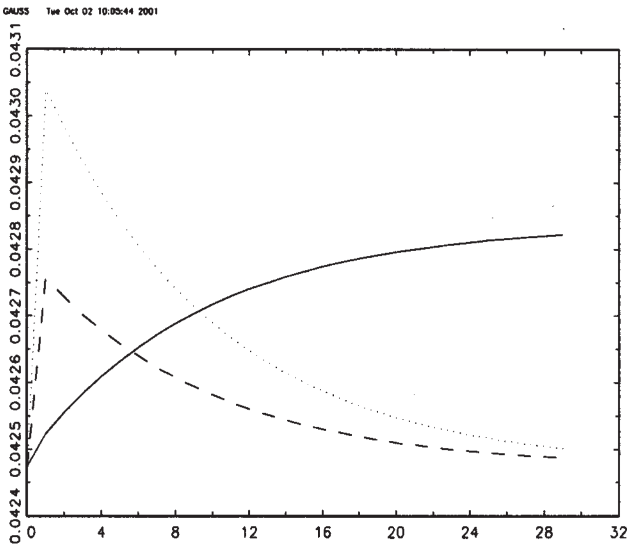
[5] For this calibration, there exists a unique steady state equilibrium with positive growth. This equilibrium is (locally) saddlepoint. Things are much more complicated in Boucekkine and de la Croix (2001).

Figure 1 : *Fraction of labor force in the software production sector*



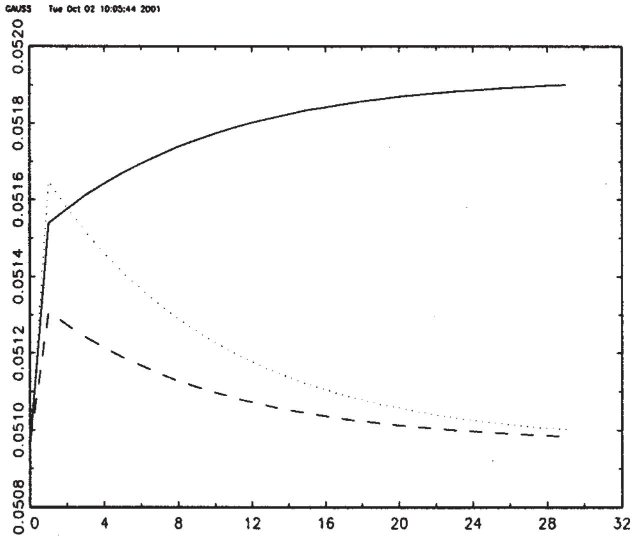
shock in the research sector (μ) : solid line.
shock in the software sector (γ) : dashed line.
shock in the capital sector (e) : dotted line.

Figure 2 : *Fraction of labor force in the R&D sector*



shock in the research sector (μ) : solid line.
shock in the software sector (γ) : dashed line.
shock in the capital sector (e) : dotted line.

Figure 3 : *Growth rate of output*



shock in the research sector (μ) : solid line.
shock in the software sector (γ) : dashed line.
shock in the capital sector (e) : dotted line.

manent IT boom is registered. A 1% shock induces an increment of the long run growth rate of output in the final good sector by 0.18 percentage points, which is highly significant as the weight of the R&D sector in the economy in terms of labor does not exceed 5% in our calibration. Productivity shocks in the production of softwares and efficient capital have no long run growth effect. From the theoretical point of view, this is not surprising if one has in mind that we are dealing with a Romer-like model. Contrary to lab-equipment models *à la* Rivera-Batiz and Romer (1991), the former implies different production technologies per sector. Therefore, if the productivity shock does not affect directly and permanently the sector responsible for long term growth, here the R&D sector, there may be no road to long term growth. We check this property here. From a practical point of view, this means that a safe diagnosis on the viability of an IT boom should identify exactly what are the mechanisms behind the boom. If it is only a huge improvement in the production of hardware as claimed by Gordon (1999), coupled with a massive capital deepening, then we should conclude with Gordon that the IT boom is going to collapse. If one has in mind the pace of the US R&D expenditures and believes in a kind of perpetual Moore's law (stating that the number of transistor on a chip doubles every two years), then he should conclude that the IT booms do have long term growth effects.

(iii) **On the intensity of the IT booms** : In all the performed experiments, it appears that the IT booms based on productivity shocks on the capital sector (e_t) are much more intense and persistent than those coming from productivity gains in the production of softwares. The short term response of the considered variables turn out to be at least twice stronger in the former case. A rise in e_t has a direct effect on the production of efficient capital, which is one of the two inputs in the production of the final good. In contrast, an increase in γ_t has only an indirect effect on the efficient capital sector, inducing a much less intense capital accumulation and therefore a much lower short term output growth rate. This enhances the role of physical capital or hardware accumulation in this type of booms. Producing softwares in bigger quantities certainly improves the efficiency of the capital goods but the growth effect associated with this configuration is not likely to be important even in the short run compared with the situation in which the accumulation of efficient capital relies on both softwares and hardware (physical capital in our model). Indeed the growth rate of the economy is even bigger under an e_t shock than under a μ_t shock in the short run since capital deepening is more intense in the former case. Our model does not deliver a *weightless economy* (using the terminology of Quah, 1999) view of an IT driven growth regime. Physical accumulation is a preeminent engine of either short term and long term growth (*via* embodiment).

4 Conclusion

This paper investigates and interprets some of the properties of a multisectoral growth model with endogenous embodied technical change in the light of the ongoing debate on the viability of an IT based growth regime. The main arguments put forward in the debate, starting with Gordon's (1999), can be recovered within our theoretical framework. In particular, we have illustrated the two main views of the 1995-2000 IT boom in the USA. If it just comes from productivity gains in the production of hardware and even though these gains are permanent, the story could be just one of temporary massive capital deepening and no long term growth effect. To get everlasting growth effects, the IT boom should rely on an ever rising productivity, i.e. a kind of perpetual Moore's law. Obviously, our model is too simple to deliver much finer messages and some crucial improvements should be achieved to this end. Our ongoing research program is pretty much concerned with a more realistic modeling of R&D competition in the information age, among other open issues.

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