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Growth leaders

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Abstract

This article presents a Schumpeterian model where the engine of growth is in the microeconomic structure of the patent races. Under decreasing marginal productivity and endogenous entry in the R&D sector, the equilibrium is characterized by small firms investing too little and the growth process is dynamically inefficient; the optimal policy for innovation always implies R&D subsidies. When the incumbent monopolists are leaders in patent races with endogenous entry, they engage in larger R&D investment and their persistent leadership enhances growth. In a multicountry setup, growth is driven by innovations in the largest country and increases with its relative size and openness. Finally, I derive the optimal R&D subsidy from the point of view of a single country, and provide a new case for international coordination of R&D policies.

JEL classification: O3; O4; F4

Keywords: Growth; Innovation

1. Introduction

The search for profits provides the incentives to invest and ultimately drives the economy. The new growth theory, starting with the works of Romer (1990) and Aghion and

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Howitt (1992), has exploited this old Schumpeterian idea to formalize the link between innovation and long-run growth. In this literature, investments for innovations are usually described in a very simple and empirically arguable way: the production function of new ideas is characterized by constant marginal productivity and a simple no-arbitrage condition pins down the equilibrium investment and, consequently, the rate of economic growth. This "minimalist" approach does not allow characterization of the number and size of the firms investing in R&D, the relation between incumbent patentholders and outsiders and the effect of realistic R&D policies. In this article, I try to open the "black box" of the engine of growth, investigating its microeconomic organization in a more general and realistic way.

As noticed in empirical studies by Kortum (1993), Griliches (1994), Cohen and Klepper (1996) and others, investments in R&D are characterized by relevant fixed costs, decreasing marginal productivity at the firm level[1], and wasteful duplication of resources between firms due to congestion reasons at the industry level. Quite surprisingly, the existing literature on Schumpeterian growth has largely ignored these features: for instance, it has always assumed constant marginal productivity of R&D investments while all the available estimates of the elasticity of innovation to R&D spending are consistently below unity (see Pakes and Griliches, 1980; Hausman et al., 1984; Blundell et al., 2002; Acemoglu and Linn, 2004). In this work, I introduce full fledged "patent races" characterized by high fixed costs of R&D, decreasing marginal productivity of investment and endogenous entry in the Schumpeterian model due to Barro and Sala-i-Martin (2004), and derive the drastic consequences associated with the inefficiency in the market for innovation. Its organization is now characterized by a bias toward small firms investing too little in R&D. This inefficiency is amplified in the growth process, which becomes dynamically inefficient, in the sense that a country could increase its long-run growth without reducing current consumption or, vice versa, increase consumption without reducing growth. Hence, contrary to the ambiguous results in the literature, the optimal R&D policy implies always R&D subsidization. In this context, I derive the optimal R&D policy which requires an R&D subsidy to achieve the efficient organization of the innovation activity and an entry subsidy or fee to achieve the optimal growth rate.

Another important stylized fact about R&D investment, documented by Malerba and Orsenigo (1999), Hughes (2007), Czarnitzki and Kraft (2007a) and others, is that a large part of it is done by dominant firms producing with the leading-edge technologies[2]. Following Etro (2004), I provide a rationale for investment by the incumbent patentholders based on their leadership and free entry in sequential patent races: when incumbents can commit to investments in R&D, they have more incentives than the other firms to invest to escape from the innovative pressure of the outsiders[3]. This paper goes beyond my previous research, where I sketched a dynamic model without solving it, and exploits

[1] One of the stylized facts pointed out by Cohen and Klepper (1996) is that the number of patents and innovations per dollar of R&D decreases with the level of R&D and this is well-grounded empirically.

[2] For related and updated research on this topic see the International Think-tank on Innovation and Competition (www.intertic.org). For recent surveys of related theoretical and empirical advances on competition and growth see Aghion and Griffith (2005).

[3] Blundell et al. (1999) provide evidence from recent high-tech sectors which is consistent with this thesis. In a similar vein, Nicholas (2003) studies 1920s America and shows that "firms with high levels of market power tended to innovate more because they had strong incentives to do so pre-emptively". Etro (2007) provides further discussion on this evidence.

the method of undetermined coefficients to analytically solve for the equilibrium growth path and the endogenous value of technological leadership. Contrary to the previous literature, I focus on the empirically relevant case of decreasing marginal productivity of R&D investment (estimates of the elasticity of innovations to R&D investment are well below unity). Such a case is characterized by both the incumbent patentholders and outsiders investing in R&D, but with the incumbents investing more than the outsiders. This investment by the incumbents leads to endogenous persistence of technological leadership, which in turn increases the value of developing innovations: this value is not simply due to the corresponding flow of profits (as traditionally in the literature), but it also includes the option value to a persistent monopolistic position. The new element increases the incentives to invest mostly for the monopolists but also for the outsiders, and hence it speeds up the growth process: in a sense, growth is driven by market leaders. This characterization of growth driven by dominant firms may help to explain the persistence of technological leadership especially for large corporations in high-tech sectors.

In a recent article, Segerstrom (2007) has provided a related analysis of growth driven by market leaders in the high-tech sectors, explicitly referring to the substantial contribution of companies like Intel, Microsoft, Motorola, Nokia, Pfizer and other technological leaders, to the global growth. He has developed a model where incumbent monopolists invest in R&D because they can use a different innovation technology from the one adopted by the other firms. The approach of Segerstrom assumes cost advantages in the innovation activity for the monopolists and allows the study of their persistence, but it does not explain its ultimate source. Aghion and Griffith (2005) develop simple models to analyze the relation between competition in the market and growth, but they assume exogenously that only the incumbent monopolist and an outsider invest in R&D. My approach has the advantage of endogenizing both the investment of the incumbents and the entry and the investment of the outsiders in the market for innovations, so as to provide a comprehensive characterization of the R&D sector.

Technological progress and growth are a global phenomenon today. Therefore, I will also extend the model to a multicountry framework with endogenous entry in the international competition for the market to verify how the incentives to invest in R&D and the effects of R&D policy are affected in an open economy framework. In the presence of trade frictions, the technological frontier shifts toward the country with the largest internal market. This country develops a comparative advantage in the R&D sector (derived from its larger internal demand) and produces advanced intermediate goods for the rest of the world. Even if stylized, this characterization of the global equilibrium is consistent with the growth experience of the last decades, and in particular with large R&D investments and technological progress in the US, high US imports of final goods which allowed other countries to import American technology and absorb its growth, and large capital flows toward the US financing its large investments. The growth rate is positively related to the degree of openness and it exhibits relative (and not absolute) scale effects: an increase in the size of the leading economy compared to the rest of the world enhances growth.

Finally, I also show that in a multicountry framework, R&D subsidization is again the optimal unilateral policy, but for different reasons than in a closed economy. When entry in the international competition for innovations is endogenous, R&D subsidies allow domestic firms to be provided with a strategic advantage, as if they were first movers able to commit to high investments in R&D, and to conquer a leadership in the world markets, but without affecting global growth. This suggests a novel case for international cooperation on R&D policy aimed at coordinating R&D subsidies.

The paper is organized as follows. Section (2) describes the model and Section (3) solves for the equilibrium organization of the R&D sector and for the general equilibrium discussing the optimal R&D policy. Section (4) endogenizes the persistence of monopolies. Section (5) extends the model to an open economy and discuss issues of R&D subsidization. Section (6) concludes. Technical details are in the Appendix.

2. The model

Let us consider an infinite horizon representative agent with isoelastic utility:

$$U = \int_0^\infty \frac{C^{1-\gamma}}{1-\gamma} \mathrm{e}^{-\rho t}\, \mathrm{d}t \tag{1}$$

where γ positive and different from 1 is the elasticity of substitution and $\rho > 0$ is the time preference rate. The representative agent earns income and chooses consumption and savings according to the usual optimality condition:

$$\frac{\dot{C}}{C} = \frac{r-\rho}{\gamma} \tag{2}$$

which holds at each point in time. Using the intertemporal resource constraint, one can derive an expression for savings depending on the expected value of income and on the interest rate profile.

Output Y can be used for consumption C, production of intermediate goods X or investment in R&D activities providing a rate of return r, and it is produced according to a generalized version of the production function introduced by Barro and Sala-i-Martin (2004, Ch. 7)[4]:

$$Y = A\left[\sum_{j=1}^{N} (q^{\kappa_j} X_j)^{\theta}\right]^{\frac{\alpha}{\theta}} L^{1-\alpha} \tag{3}$$

where A is total factor productivity, L is the fixed labor force, X_j is the intermediate good j of quality κ_j, which is assumed non-durable for simplicity, N is the constant number of intermediate goods, $q > 1$ and $0 < \alpha \leqslant \theta \leqslant 1$. It can be easily verified that this function satisfies constant returns to scale and decreasing marginal productivity of each input. The parameter α represents the factor share of income from intermediate goods while $1-\alpha$ is the labor share. The parameter θ reflects the elasticity of substitution between intermediate inputs, with $1/(1-\theta)$ approximating the elasticity of demand for each intermediate good. In the standard literature, these two parameters are equated setting $\alpha = \theta$, as in Barro and Sala-i-Martin (2004), while it is important to keep them separate.

The market for the final good, which is the *numeraire*, and the markets for labor and credit (to firms investing in R&D) are perfectly competitive. This is not the case in the market for intermediate goods, that are only imperfect substitute. Each intermediate good is

[4] An advantage of this framework is that technological progress due to innovations realizes independently for each intermediate good: hence, it allows to think of small and frequent innovations rather than innovations for general purpose technologies.

sold by a single producer until a newer version is on the market, which is a reasonable situation when the rate of creation of new products is fast enough[5]. The cost of production of intermediate goods is characterized by a unitary marginal cost and, eventually, a fixed cost of production. The demand of these inputs from the final good producers can be derived from (3)[6], and, under both competition in quantities and prices, the equilibrium price of the intermediate goods can be derived as a usual mark-up rule on the unitary marginal cost:

$$p(\kappa_j) = \frac{1}{1 - \frac{1}{\epsilon(N)}} \tag{4}$$

where $\epsilon(N)$ is the elasticity of demand, increasing in the number of producers. Since the price and the profits of the firms producing intermediate goods are both decreasing in their number, eventual fixed costs of production would allow to endogenize entry and to pin down the equilibrium number of inputs N^*. Notice that a slow growth of these fixed costs and an exogenous growth of TFP and of the labor force are a source of endogenous growth, similarly to Romer (1990), but here we will neglect this possible source of growth. Moreover, shocks to the fixed costs of production and shocks to TFP are an interesting source of business cycles: endogenous entry is an additional element of propagation of the business cycle[7].

As well known, under both price and quantity competition, when the number of intermediate goods is high enough (that strategic interactions are negligible) or in the particular case with $\alpha = \theta$[8], the optimal price of each intermediate good is $1/\theta$ if innovations are drastic (because $\epsilon(\infty) \to 1/(1-\theta)$), which requires $q > 1/\theta$. We will assume that this is the case, so that the mark-up is $(1-\theta)/\theta$[9]. Then, the aggregate quantity produced of intermediate good j can be determined as:

$$X(\kappa_j) = (\alpha\theta A)^{\frac{1}{1-\theta}} L^{\frac{1-\alpha}{1-\theta}} q^{\frac{\kappa_j \theta}{1-\theta}} Q^{-\frac{\theta-\alpha}{\theta(1-\alpha)}} \tag{5}$$

where we have introduced the Barro and Sala-i-Martin aggregate quality index $Q \equiv \sum_{j=1}^{N} q^{\frac{\kappa_j \alpha}{1-\alpha}}$. Substituting the quantity $X(\kappa_j)$ from (5) in the production function (3), we obtain the output of final goods:

[5] According to the empirical evidence surveyed by Cohen and Klepper (1996), whether major or incremental and whether patented or not, innovations grant market advantage “within one year for many industries and within three years for most”.

[6] Inverse demand for input j is:

$$p(\kappa_j) = \frac{\alpha A q^{\kappa_j \theta} L^{1-\alpha} X_j^{-(1-\theta)}}{\left[\sum_{j=1}^{N} (q^{\kappa_j} X_j)^{\theta}\right]^{\frac{\theta-\alpha}{\theta}}}$$

which is decreasing in the output of each intermediate good, and increasing in TFP and labor force.

[7] A positive shock as a reduction in the fixed costs induces endogenous entry which reduces the endogenous mark up according to (4). The same effect is induced by a positive shock to TFP: in such a case, the positive shock is amplified by the induced reduction in the markups associated with the increased entry. Endogenous entry in product markets has been largely neglected in the neoclassical and newkeynesian literatures on business cycles.

[8] This happens when the fixed costs of production are negligible.

[9] The case of non-drastic innovations emerges for $q < 1/\theta$ and implies that each producer of intermediate goods applies the limit price q (see for instance Barro and Sala-i-Martin (2004). In such a case, the rest of our analysis goes through in a similar fashion taking into account this price for the intermediate goods.

$$Y = (\alpha\theta)^{\frac{\alpha}{1-\alpha}} A^{\frac{1-\theta+\alpha}{1-\theta}} L^{1+\frac{\alpha(\theta-\alpha)}{1-\theta}} Q^{\frac{\alpha(1-\theta)}{\theta(1-\alpha)}} \tag{6}$$

and the total amount of intermediate goods $X = \alpha\theta Y$. Since TFP and labor force are constant, the growth rate of income must be:

$$g \equiv \frac{\dot{Y}}{Y} = \frac{\alpha(1-\theta)}{\theta(1-\alpha)} E\left[\frac{\dot{Q}}{Q}\right] \tag{7}$$

where the last term is the expected growth rate of the aggregate quality index.

To describe the investment side of the economy, we need to describe the technology to create innovations. When an innovation for an intermediate good j generates the new quality rung κ_j, the innovator starts producing with the cutting-edge technology and obtains a flow of profits $(1-\theta)X(\kappa_j)/\theta$. At the same time the race to find out the subsequent innovation begins. To participate, any firm i has to pay a fixed cost $F(k_j)$, which may include an entry fee set by the government, and spend a flow of resources $z_i(\kappa_j)$. Finally, for any unit of investment, there is a subsidy at rate s financed with lump sum taxes.

The technology for the invention of new goods allows for decreasing marginal productivity at the firm level. In particular, the investment for firm i gives birth to the innovation k_j according to a Poisson process with arrival rate $p_i(\kappa_j)$ given by a concave function of $z_i(\kappa_j)$. To obtain closed form solutions, I assume the following specification:

$$p_i(\kappa_j) = [\phi(\kappa_j)z_i(\kappa_j)]^{\epsilon} \tag{8}$$

where the function $\phi(\kappa_j)$ expresses how difficult is to discover technology κ_j and $\epsilon \in (0,1)$ represents the elasticity of expected revenue with respect to the flow of investment. This parameter is unitary in the existent versions of the quality-ladder model, implying constant marginal productivity (equivalent to constant returns to scale since there is just one input) in the R&D sector, but a wide empirical research suggests an elasticity much smaller than 1[10].

To have an idea of the realistic shape of this function, notice the first estimate of the elasticity of the number of innovations with respect to investment in R&D by Pakes and Griliches (1980) was 0.6, the time series study of Hausman et al. (1984) estimated an elasticity of 0.87 using the Poisson distribution, decreased at 0.5 with the larger sample used by Hall et al. (1986), Kortum (1993) suggested a range between 0.1 and 0.6 and Blundell et al. (2002) found a long-run elasticity close to 0.5. Most of these estimates were based on the relation between investment and number of patented innovations, which is not necessarily a good measure of innovation (since only a small percentage of patents are really valuable). Recently, Acemoglu and Linn (2004) have focused on the new drugs obtained in the pharmaceutical industry (rather than the new patents) obtaining an implicit estimate of the elasticity of the innovations with respect to R&D investment around 0.8[11].

The arrival rate of innovation κ_j, is the sum of the individual arrival rates of the $n(\kappa_j)$ entrants plus the one of the incumbent, indexed with M, $p(\kappa_j) = \sum_{i=1}^{n(\kappa_j)} p_i(\kappa_j) + p_M(\kappa_j)$.

[10] Notice that from a theoretical point of view, notice that, while in most of the productive sectors there are good reasons to believe that doubling the amount of input total production will double, there are no reasons to believe that doubling the amount of inputs in the R&D activity will double the expected amount of innovations, and even Aghion and Howitt (1998, Ch. 12) accept this as a stylized fact – see also Scotchmer (2004).

[11] Notice that Segerstrom (2007) assumes $\epsilon = 0.3$ in his model, an elasticity below the typical estimates.

Using the properties of Poisson processes in a standard fashion, this implies that the expected discounted value of the profits with innovation κ_j is:

$$V(\kappa_j) = \left(\frac{1-\theta}{\theta}\right)\frac{X(\kappa_j)}{r+p(\kappa_j)} \tag{9}$$

where $r + p(\kappa_j)$ is a sort of effective discount factor. Moreover, the expected net profit of entrant i in the patent race in sector j when the current quality is κ_j can be written as:

$$\Pi^i(\kappa_j) = \frac{[\phi(\kappa_j)z_i(\kappa_j)]^\epsilon \mathbf{V}^M(\kappa_j+1) - (1-s)z_i(\kappa_j)}{r+p(\kappa_j)} - F(\kappa_j) \tag{10}$$

where $\mathbf{V}^M(\kappa_j + 1)$ is the value of being monopolist with the next technology $\kappa_j + 1$. Since also the incumbent monopolist with the technology κ_j can invest to innovate, we need to consider its objective function, which is given by a Bellman equation defining the value of being such a monopolist[12]:

$$\mathbf{V}^M(\kappa_j) = \max_{z_M \geqslant 0}\left\{V(\kappa_j) + \frac{[\phi(\kappa_j)z_M]^\epsilon \mathbf{V}^M(\kappa_j+1) - (1-s)z_M}{r+p(\kappa_j)} - F(\kappa_j)\right\} \tag{11}$$

where the fixed cost is paid only if $z_M > 0$ and $V(\kappa_j)$ is given by (9). This value is the core of the engine of growth, because what drives investment and growth is exactly the attempt to conquer it. In the standard literature, monopolists do not invest, hence the value of becoming a monopolist is just the expected profit from the next innovation. However, as we will see later on, monopolists invest when they have a leadership in the patent race and in that case, the value of the innovation includes also the option value of a persistent monopoly, which fundamentally modifies the incentives to do research.

Finally, following Barro and Sala-i-Martin (2004), I assume that new ideas are more difficult to obtain when the scale of the sector increases, and, following Etro (2004), I assume that the fixed cost of R&D increases with subsequent innovations and corresponds to a constant fraction of the expected cost of production with the new technology. More precisely, I assume that $\phi(\kappa_j) = [\zeta\ X(\kappa_j + 1)]^{-1}$ and $F(\kappa_j) = \eta\int_0^\infty X(\kappa_j + 1)\mathrm{e}^{-[r+p(\kappa_j+1)]t}\,\mathrm{d}t$ with $\zeta > 0$ and $\eta \in (0, \mu)$. I want to capture the idea that the larger is the scale of expected production of a firm, the larger are the costs necessary to discover and develop the associated technology: construction of prototypes and samples, new assembly lines and training of workers. These assumptions guarantee that spending in R&D increases at the same rate as output, delivering a balanced growth path without scale effects, in line with the last generation of quality-ladder models (see Jones, 1995; Barro and Sala-i-Martin, 2004). The intuition relies on the fact that the growth rate must be associated with a constant rate of investment in R&D. In the presence of fixed costs of R&D, this requires that subsequent innovations need fixed costs that are increasing in the size of the economy. As a consequence of these assumptions, increases in the labor force have the same proportional impact on output and R&D spending, so that the rate of innovation and the growth rate are not affected. Therefore, there are no scale effects[13].

[12] Notice that the associated no-arbitrage condition under optimal behavior implies the standard equivalence between the riskless return rate and the expected return rate from R&D investment of a monopolistic firm.

[13] See Peretto and Connolly (2005) for a related discussion on the role of fixed costs of R&D in Schumpeterian models.

To close the model, the expected growth rate of the quality index will be derived as:

$$E\left[\frac{\dot{Q}}{Q}\right] = p\left[q^{\frac{\theta}{1-\theta}} - 1\right] \approx \frac{p\theta \ln q}{1-\theta}$$

where $p \equiv [\sum_{j=1}^{N} p(\kappa_j) q^{\frac{\kappa_j \theta}{1-\theta}}]/Q$ is a weighted average of the probability of innovations, and we used the approximation $\ln(1+x) \approx x$ which holds for x small enough. Accordingly, the growth rate of income simplifies to:

$$g \approx \frac{\alpha(1-\theta)}{\theta(1-\alpha)} \left(\frac{p\theta \ln q}{1-\theta}\right) = \frac{p\alpha \ln q}{1-\alpha} \tag{12}$$

which depends on the factor shares and not on the elasticity of substitution between intermediate goods.

Given this setup, one can study different organizations of the market for innovations[14]. In this article I will consider first the traditional case of Nash competition with endogenous entry and, later on, the more realistic case of Stackelberg competition with endogenous entry, in which the current monopolist has a first mover advantage.

3. Dynamic inefficiency and R&D policy

In this section, I model competition in the market for innovation in the Nash fashion. As well known since Arrow (1962), under free entry the leader does not invest, because its best strategy is to stay out from the patent race and enjoy the profits from its current product until a new innovation will make it obsolete. Competition for innovations is just between outsiders and the scope of this section is to characterize the equilibrium organization of the market for innovations – the number of firms and the size of their investments – together with the usual macroeconomic variables and to derive the optimal R&D policy.

Consider the competition in a generic sector κ for the j innovation. Under Nash competition[15], the lack of investment by incumbents implies that the value of being a monopolist (11) boils down to $\mathbf{V}^M(\kappa_j) = V(\kappa_j)$. Each firm chooses its investment $z_i(\kappa_j)$ to maximize (10) taking as given the strategies of the other firms, the value of the next innovation and the interest rate, while the free entry condition sets the expected profits (10) equal to zero providing the equilibrium number of entrants $n(\kappa_j)$. Combining the optimality condition and the free entry condition we obtain the investment per firm:

$$z(\kappa_j) = \epsilon^{\frac{1}{1-\epsilon}} \phi(\kappa_j)^{\frac{\epsilon}{1-\epsilon}} \left(\frac{V(\kappa_j+1) - F(\kappa_j)}{1-s}\right)^{\frac{1}{1-\epsilon}} \tag{13}$$

which is increasing in the subsidy and in the value of the innovation net of the fixed cost of entry, while it is independent from the interest rate.

Using the endogenous value of innovation (9) and our functional form assumptions in (13) and substituting in the free entry condition, which sets (10) equal to zero, we can express the effective discount factor as:

[14] A related investigation is present in a work by Zeira (2003). However, his interest is in the choice of innovators between simple innovations and more difficult but radical innovations and across multiple research strategies.

[15] See Etro (2007) for a survey on Nash equilibria with free entry and for many applications.

$$p(\kappa_j)+r=\frac{[\phi(\kappa_j)z(\kappa_j)]^{\epsilon}V(\kappa_j+1)-z(\kappa_j)}{F(\kappa_j)}$$
$$=\frac{[\phi(\kappa_j)X(\kappa_j+1)]^{\frac{\epsilon}{1-\epsilon}}\left[\epsilon^{\frac{\epsilon}{1-\epsilon}}\left(\frac{1-\theta}{\theta}-\eta\right)^{\frac{\epsilon}{1-\epsilon}}\left(\frac{1-\theta}{\theta}\right)-\epsilon^{\frac{1}{1-\epsilon}}\left(\frac{1-\theta}{\theta}-\eta\right)^{\frac{1}{1-\epsilon}}\right]}{\eta[r+p(\kappa_j)]^{\frac{\epsilon}{1-\epsilon}}(1-s)^{\frac{\epsilon}{1-\epsilon}}}$$
$$=\left[\frac{\epsilon(1-\theta-\eta\theta)}{\bar{\zeta}(1-s)\theta}\right]^{\epsilon}\left[\frac{(1-\theta)(1-\epsilon)+\epsilon\eta\theta}{\eta\theta}\right]^{1-\epsilon}\qquad\text{for any }\kappa_j$$

which simplifies to a constant probability of innovation p linearly decreasing in the interest rate[16]:

$$p=\frac{1}{\theta}\left[\frac{\epsilon(1-\theta-\eta\theta)}{\bar{\zeta}(1-s)}\right]^{\epsilon}\left[\frac{(1-\theta)(1-\epsilon)+\epsilon\eta\theta}{\eta}\right]^{1-\epsilon}-r \tag{14}$$

where $\bar{\zeta}=\zeta\theta^{-1/(1-\theta)}$. This equation provides an implicit equilibrium relation between the interest rate and the investment in innovation, which is expressed in terms of the aggregate probability of innovation that firms can support. Of course, a higher interest rate reduces the incentives to invest in R&D since it increases the return on alternative investments.

Using (14), we can obtain an explicit expression for the expected value of innovation (9), and substituting in (13) again, we obtain the equilibrium flow of investment per firm:

$$z(\kappa_j)=\frac{\epsilon\eta(1-\theta-\eta\theta)}{[(1-\theta)(1-\epsilon)+\epsilon\eta\theta](1-s)}q^{\frac{\theta}{1-\theta}}X(\kappa_j) \tag{15}$$

which is increasing in the quality achieved in the single sector, since this implies higher demand and hence higher expected profits for the corresponding intermediate product, and increasing in the degree of returns to scale, ϵ, since this makes investment more productive. For a given scale of production, investment is also increasing in the mark up (decreasing in θ), which is exactly at the core of the Schumpeterian idea that monopolistic profits drive investment of single firms[17]. Finally, the interest rate does not affect the individual investment of firms, while it negatively affects the number of firms and hence the total investment. This result is quite intriguing: any adjustment of R&D investment to variations in the interest rate goes through changes in the number of firms, not in their size.

The decentralized equilibrium does not optimizes the allocation of investment across firms in the sense that it does not minimize R&D expenditure for a given probability of innovation. In particular, we can easily derive the investment per firm which minimizes total expected costs (fixed and variable) for a given probability of innovation (in the Appendix A, I show that the social planner solution results in the same organization). If the investment flow is $\beta X(\kappa_j+1)$ for each firm, the efficient organization chooses β to minimize expenditure $(\beta+\eta)X(\kappa_j+1)$ for a given probability of innovation $[\phi(\kappa_j)\beta X(\kappa_j+1)]^{\epsilon}$. This generates the following investment:

[16] In the Barro and Sala-i-Martin (2004) model, the arbitrage equation for the patent race κ_j pins down the investment in innovation in the patent race κ_j+1 with a weak economic intuition. Instead, here the free entry condition for the patent race κ_j pins down the number of firms investing in innovation in the patent race κ_j and, together with their profit maximizing choices, their individual investments in the same patent race κ_j.

[17] The effect of higher fixed costs on investment can be shown to be non-monotonic, positive for η low but negative for η high enough: on one side high fixed costs reduce expected profits for a given life of the patent, but on the other, they reduce the innovation rate in the future so as to increase the expected life of the patent.

$$z^*(\kappa_j) = \frac{\epsilon\eta}{1-\epsilon} q^{\frac{\theta}{1-\theta}} X(\kappa_j) \tag{16}$$

which is larger than (15) in the absence of subsidization: in a decentralized equilibrium firms tend to choose inefficiently small investments. The intuition relies on the fact that researchers do not internalize the effect of their choices on the entry decision, and entry creates wasteful duplication of R&D expenditures, in terms of fixed costs of research: hence, *ceteris paribus*, firms choose suboptimal investment. Since growth depends on the probability of innovation, the equilibrium is dynamically inefficient: the economy could achieve the same aggregate probability of innovation investing a smaller amount of total resources or increase the former at the same level of the latter. This leads to a crucial property of the equilibrium organization of the R&D sector:

Proposition 1. *Under Nash competition in the market for innovations, the equilibrium implies a sub-optimal flow of investment in R&D per firm and dynamic inefficiency in the growth process.*

This form of dynamic inefficiency is absent in traditional models of endogenous growth, where the economy may grow above or below an optimal benchmark, but cannot increase the growth rate without giving up to some of the current consumption: when marginal productivity in the R&D sector is decreasing, the endogenous organization of this sector creates this inefficiency. Only a proper R&D policy can solve it and, using (15) and (16), one can easily derive the subsidy which induces the optimal investment per firm in the decentralized equilibrium:

$$s^* = \frac{\eta\theta}{(1-\theta)(1-\epsilon) + \eta\epsilon\theta} \in (0,1) \tag{17}$$

which is always positive and increasing in θ and η, since higher effective markups already create larger investments.

On a balanced growth path with a constant interest rate, the resource constraint implies that income, investment and hence consumption must grow at the same rate. Equating (2) and (12) one obtains an implicit expression for the savings that the agent is willing to provide at a given interest rate, expressed in terms of the aggregate probability of innovation that these savings can support:

$$p = \frac{(1-\alpha)(r-\rho)}{\alpha \ln q} \tag{18}$$

Of course, a higher interest rate increases the incentives to save, and hence it increases the probability of innovation that savings can support.

Market clearing in the credit market derives from the equality of the two relations between the interest rate and the probability of innovation (14) and (18), and provides the equilibrium interest rate and the growth rate of the economy:

$$g = \frac{\left[\frac{\epsilon(1-\theta-\eta\theta)}{\zeta(1-s)\theta}\right]^{\epsilon}\left[\frac{(1-\theta)(1-\epsilon)+\epsilon\eta\theta}{\eta\theta}\right]^{1-\epsilon} - \rho}{\gamma + (1-\alpha)/\alpha \ln q} \tag{19}$$

First of all, notice that the role of the factor share of intermediate goods α and of the elasticity of substitution between these goods is separated: growth is increasing in the former and decreasing in the latter (while the two parameters were identical in the traditional Barro and Sala-i-Martin formulation). As one could expect, the higher is the mark up (lower θ) and the less costly are innovations (lower η and ζ), the higher is equilibrium growth. Finally, the relation between growth and ϵ is U-shaped. Notice that, as expected, the model does not exhibit scale effects since the growth rate does not depend on the size of the population, in line with well known empirical evidence (Jones, 1995). Notice that introducing positive growth of the labor force, we would obtain a growth rate of per capita income which would be linearly increasing in population growth[18].

The dynamic inefficiency of the growth process shows that a country with an industrial structure characterized by small firms engaged in R&D achieves inefficient results, and could grow more without losses in the production of final goods (for consumption) if its firms were investing more individually in R&D. This general conclusion may shed new light on the problems of countries that do not grow much and lack large and innovative corporations.

The equilibrium arrival rate of innovations is directly proportional to the above growth rate, while the endogenous number of firms can be derived as:

$$n = \frac{\left[\frac{(1-\theta)(1-\epsilon)+\epsilon\eta\theta}{\eta\theta}\right] - \rho\left[\frac{\bar{\zeta}[(1-\theta)(1-\epsilon)+\epsilon\eta\theta](1-s)}{\epsilon\eta(1-\theta+\eta\theta)}\right]^{\epsilon}}{1+\alpha\gamma\ln q/(1-\alpha)} \tag{20}$$

Notice that while the growth rate is increasing in the size of innovations q, the number of firms is decreasing in it. Hence larger size innovations are associated with higher growth but fewer firms investing in them: of course, this is possible because each firm invests more in R&D.

Clearly, a social planner would choose the number of firms investing in R&D and consequently the growth rate of the economy taking into account the social value of innovations, rather than their private value, and in the Appendix I show that in equilibrium both n and g are suboptimal at least for γ small enough. This result has a simple intuition: when the intertemporal elasticity of substitution is large (γ is low), it is optimal to choose a high growth rate of consumption, therefore, the social value of innovations is high. On the other side, the private value of innovations depends on market features which are independent from consumers preferences (except for an indirect channel going through the interest

[18] Consider a positive rate of growth of the labor force L, say $g_L = \dot{L}/L$. The expected discounted value of the profits with innovation k_j at time t becomes:

$$V_t(\kappa_j) = \frac{\left(\frac{1-\theta}{\theta}\right)\left(\frac{\alpha q^{\kappa_j \alpha} A}{1+\mu}\right)^{\frac{1}{1-\alpha}} L_t}{r + p(\kappa_j) - g_L}$$

which increases in g_L. The equilibrium in the market for innovations can be derived as before. Since the size of the economy is growing at the constant rate, firms choose an investment in R&D growing at a constant rate as well, and the equilibrium number of firms is fixed and endogenously dependent on g_L. On the balanced growth path output must still grow at the same rate as consumption, therefore, the equilibrium growth rate can be derived as:

$$g(g_L) = g(0) + \frac{g_L \alpha \ln q}{1-\alpha+\gamma\alpha\ln q}$$

which is linearly increasing in the growth rate of population. Summarizing, an increase in the population growth rate increases the number of firms investing in innovation and total investment in innovation.

rate). Accordingly, for γ small enough, the social value of innovations is higher than the private value and the optimal number of firms becomes larger than the equilibrium one.

The optimal allocation of resources can be achieved with two policy tools derived in the Appendix, a positive R&D subsidy, which optimally allocates resources between investors and an entry subsidy (or a fee for γ large enough) which targets the optimal number of firms[19]:

Proposition 2. *The optimal R&D policy requires a positive R&D subsidy to investment and an entry subsidy/fee to achieve the optimal organization of the market for innovations and the optimal growth rate.*

The message of this section is quite in contrast with the usual models of Schumpeterian growth, where the optimal R&D policy may imply taxation or subsidization of the R&D investment (see Grossman and Helpman, 1991 or Barro and Sala-i-Martin (2004). When we take into account the organization of the market for innovations, we obtain a more intuitive result, for which innovating firms should always be subsidized (to increase their size), even when growth is too high.

4. Growth driven by market leaders

Many product innovations are due to market leaders and a lot of the investment in R&D is actually done by both incumbent monopolists and new firms. We have evidence both from patented innovations and expenditure on licenses. The comprehensive study by Malerba and Orsenigo (1999) on EU patents provides clear evidence on this point. For instance, they show that the percentage of patents granted to firms that had already innovated within their sectors is 70% in Germany, 68% in US, 62% in Japan, 60% in France, 57% in UK and 39% in Italy; moreover, they conclude that "a large fraction of new innovators is composed by occasional innovators that exit soon from the innovative scene... Only a fraction of entrants survives and grows larger (in terms of patents) as times goes by: they become persistent innovators. Older firms who survive and continue to patent are few in number but represent an important contribution to total patenting activities in any period. Here, cumulativeness of knowledge and competencies play a major role in affecting the continuity of innovative activity of these firms.". Czarnitzki and Kraft (2007a) is the first study looking at who purchases licenses on patents: on the basis of German data they show that incumbents invest more in licensing expenditures than effective and potential entrants, and more so when competitive pressure is stronger[20]. Nevertheless,

[19] Only in the limiting case of constant returns to scale, which is the traditional focus of this literature, the size and the number of firms do not matter and an R&D subsidy alone can achieve optimality. Notice that approaching constant returns to scale in our model (that is when $\epsilon \to 1$ and $\eta \to 0$), the investment by each firm and the number of firms become indeterminate, but the equilibrium growth rate converges to the traditional one (see Barro and Sala-i-Martin, 2004):

$$g \to \frac{\frac{1-\theta}{\zeta\theta(1-s)} - \rho}{\gamma + (1-\alpha)/\alpha \ln q}$$

[20] For further empirical evidence and discussion on this classic Schumpeterian insight see for instance Blundell et al. (1999), Cozzi (2007) and Segerstrom (2007).

existing models about innovation and growth are inconsistent with the simple fact that incumbent monopolists do invest in R&D, since under Nash competition and free entry, as we have seen in the previous Section (3), an incumbent monopolist has no incentives to invest in R&D.

Recent research has rationalized investment of the incumbents in a partial equilibrium framework showing that monopolists invest in R&D more than any other firm as long as they are leaders in the sense of Stackelberg in markets for innovation where entry is endogenous[21]. Actually, this behavior of the leaders under endogenous entry is a particular case of a much more general result established in Etro (2008, 2006a,b) where I have shown that Stackelberg leaders are always aggressive (under quantity or price competition or in patent races as here) whenever entry is endogenous. Here, the requirement that incumbents are leaders in the market for innovations is realistic: after all, it is reasonable to imagine that they have a credible commitment to invest a certain amount of resources to improve their own products and protect their own rents. Otherwise, we can imagine that incumbent monopolists can undertake some preliminary investments which affect their profitability from engaging in R&D activity, like building laboratories, hiring researchers or borrowing to invest[22].

Let us consider the market for innovation described in Section (2), where (10) and (11) are the objective functions of the entrants and the leader, and the latter has a first mover advantage (for simplicity, I will now abstract from the subsidies). The market for each innovation and each intermediate good works in the same way as in the partial equilibrium context characterized by Etro (2008). In particular, when ϵ is large enough incumbent monopolists deter entry obtaining complete persistence of their leadership, while for smaller values of ϵ they allow entry but invest more than any outsider[23]. Since the second case is more realistic, and since it is associated with realistic values of the elasticity ϵ (which is empirically below unity), we will focus on this case.

Consider a Stackelberg equilibrium with free entry in the market for innovation j for the intermediate good κ. The free entry condition pins down the number of followers in each sector. It is easy to verify that their optimal strategy $z(\kappa_j)$ is always independent from the one of the leader (while the number of followers decreases in the investment of the leader), hence the effective discount rate $r + p(\kappa_j)$ must be also independent from the leader's strategy (Etro, 2004). The leader chooses its investment $z_M(\kappa_j)$ to solve the problem (11), where the effective discount rate is independent from its choice and hence taken as given. From the first order conditions of the leader and of the followers, and from the zero profit condition, we obtain:

$$z(\kappa_j) = \frac{\{\epsilon\phi(\kappa_j)[\mathbf{V}^M(\kappa_j+1) - F(\kappa_j)]\}^{\frac{1}{1-\epsilon}}}{\phi(\kappa_j)} < z_M(\kappa_j) = \frac{[\epsilon\phi(\kappa_j)\mathbf{V}^M(\kappa_j+1)]^{\frac{1}{1-\epsilon}}}{\phi(\kappa_j)} \tag{21}$$

[21] See Etro (2004). For related theoretical works, see Zigic et al. (2006), Denicolò and Zanchettin (2006), Minniti (2006), Cozzi (2007), Czarnitzki and Kraft (2007b) and De Bondt and Vandekerckhove (2007).

[22] As I have shown in a more general context (see Etro (2008, 2007)), this kind of strategic investment allows to reproduce similar outcomes to Stackelberg equilibria with free entry: leaders always overinvest strategically to be aggressive in the market for innovations afterward.

[23] Segerstrom (2007) has criticized my approach for implying a low persistence of monopolies. However, my approach is even consistent with complete persistence (for ϵ high enough). Nevertheless, in a realistic setup monopolies should be persistent, not eternal.

Notice that the investment of each follower is increasing in the value of the leadership net of the fixed cost, while the investment of the leader is independent from the fixed cost. The characterization of the equilibrium is complicated by the fact that now we do not know what is the value of being a monopolist, since this is the solution to the Bellman equation (11). However, this value is what drives the incentives to invest in innovation, that is the engine of growth. In what follows I will use the method of undetermined coefficients to solve analytically this problem. Notice that such a problem will emerge whenever one is dealing with Schumpeterian models of growth where incumbent monopolists engage in R&D activity, hence this solution could be useful for future research – see Segerstrom (2007) for an alternative approach.

To derive the balanced growth path and the equilibrium value function $\mathbf{V}^M(\kappa_j)$, the functions $z(\kappa_j)$ and $z_M(\kappa_j)$ and the equilibrium values for g, r, p and n, we can guess a functional form for the value function as:

$$\mathbf{V}^M(\kappa_j) = \mathbf{V}^M(\kappa_j - 1)q^{\frac{\alpha}{1-\alpha}} = \psi\frac{X(\kappa_j)}{r+p} \tag{22}$$

where ψ is a coefficient to be determined, which can be interpreted as the rate of return from leadership. This must be larger than the basic mark up from the current innovation $(1-\theta)/\theta$, otherwise the value of being a leader investing in R&D would be smaller than the value of being a leader without investing (i.e., it would be optimal to stay out of the patent race for the leader). Substituting in (21), this implies:

$$z(\kappa_j) = \left(\frac{\epsilon(\psi-\eta)}{\bar{\bar{\zeta}}^{\epsilon}(r+p)}\right)^{\frac{1}{1-\epsilon}} q^{\frac{\alpha}{1-\alpha}}X(\kappa_j), \quad z_M(\kappa_j) = z(\kappa_j)\left(\frac{\psi}{(\psi-\eta)}\right)^{\frac{1}{1-\epsilon}} \tag{23}$$

and, using this in the Bellman equation (11), we have:

$$\begin{aligned}\mathbf{V}^M(\kappa_j) &= \frac{\left[\phi(\kappa_j)z_M(\kappa_j)\right]^{\epsilon}\mathbf{V}^M(\kappa_j+1) - z_M(\kappa_j)}{r+p} + V(\kappa_j) - F(\kappa_j) \\ &= \frac{X(\kappa_j)}{r+p}\left[\frac{1-\theta}{\theta} + \left(\frac{\epsilon}{\bar{\bar{\zeta}}}\right)^{\frac{\epsilon}{1-\epsilon}}\left(\frac{\psi}{r+p}\right)^{\frac{1}{1-\epsilon}} q^{\frac{\theta}{1-\theta}}(1-\epsilon) - \eta q^{\frac{\theta}{1-\theta}}\right]\end{aligned} \tag{24}$$

whose right hand side contains the sum of the mark up from the current innovation and another term which represents the option value of remaining monopolist after the next innovation: this option value is positive because of the leadership advantage. Using (22) and solving (24) for the effective discount rate we have:

$$r+p = \left(\frac{\epsilon}{\bar{\bar{\zeta}}}\right)^{\epsilon}\left[\frac{(1-\epsilon)q^{\frac{\theta}{1-\theta}}}{\psi-(1-\theta)/\theta+\eta q^{\frac{\theta}{1-\theta}}}\right]^{1-\epsilon}\psi \tag{25}$$

which provides a negative relation between the effective discount rate $r+p$ and the rate of return from leadership ψ (for ψ small enough): the higher is the effective discount rate, the shorter is the lifetime of an innovation, and hence the lower is the value from being a leader.

Moreover, the zero profit condition for the followers provides another expression for the effective discount rate which is analogous to (14):

$$r + p = \left[\frac{\epsilon(\psi - \eta)}{\bar{\zeta}}\right]^{\epsilon}\left[\frac{\psi(1-\epsilon) + \epsilon\eta}{\eta}\right]^{1-\epsilon} \tag{26}$$

This is a positive relation between the effective discount rate $r + p$ and the rate of return from leadership ψ: the higher is the value of being a leader, the larger will be the investment in R&D and hence the probability of innovation and the effective discount rate.

Equating (25) and (26) we obtain the equilibrium value for ψ which provides all the equilibrium relations. An implicit expression for ψ is given by:

$$\psi = \frac{1-\theta}{\theta} + \eta q^{\frac{\theta}{1-\theta}}\left[\frac{(1-\epsilon)\eta q^{\frac{\theta}{1-\theta}}\psi^{\frac{1}{1-\epsilon}}}{(\psi-\eta)^{\frac{\epsilon}{1-\epsilon}}[\psi(1-\epsilon)+\epsilon\eta]} - 1\right] > \frac{1-\theta}{\theta} \tag{27}$$

which immediately implies:

Proposition 3. *Under Stackelberg competition in the market for innovations, the equilibrium rate of return from leadership is higher than under pure Nash competition because of the option value of monopoly persistence.*

Using (26), this implies that the effective discount rate and hence both the growth rate and the aggregate probability of innovation must be higher than under Nash competition[24]. The incumbency advantage adds power to the engine of growth because it endogenously increases the value of innovations associating with them an option to persistent leadership: this increases aggregate investment and hence growth. Moreover, we can easily verify that both the return from leadership ψ, the effective discount rate and hence the growth rate are increasing in the mark up. An increase in the fixed cost of innovation through η decreases the effective discount rate and hence the growth rate of the economy, but it has ambiguous effects on the value of being a leader. Finally, when innovations are more difficult to obtain because of an increase in ζ, the value of being a leader is unchanged, but the growth rate is ultimately reduced. In conclusion, for ϵ small enough, under Stackelberg competition in the market for innovations, monopolists invest in R&D more than any outsider and the equilibrium growth rate is:

$$g = \frac{(\epsilon/\bar{\zeta})^{\epsilon}(1-\epsilon)^{1-\epsilon}\left(\eta + \frac{\psi-(1-\theta)/\theta}{q^{\theta/(1-\theta)}}\right)^{\epsilon-1}\psi - \rho}{\gamma + (1-\alpha)/\alpha \ln q} \tag{28}$$

where ψ, given by (27), is decreasing in ζ, θ and η, and we have:

Proposition 4. *Under Stackelberg competition in the market for innovations, the equilibrium growth rate is higher than under pure Nash competition.*

Clearly, when the engine of growth is given by persistent monopolistic positions as in this model, the investment by each firm increases, but it is still below the optimal level for both the incumbent monopolists and the outsiders: the dynamic inefficiency is still present. It can be shown that the optimal allocation of resources can be achieved with a positive subsidy for the entrants, a smaller but positive subsidy for the incumbent

[24] Paradoxically, even if the rate of return from leadership is higher when growth is driven by monopolists, one can easily verify that the equilibrium value of innovation is smaller. The reason is that larger investments in R&D reduce the lifelength of new intermediates.

monopolists and an appropriate entry fee to discipline entry. In particular, defining s the subsidy for the followers and s_M the one for the leaders, efficiency requires:

$$s^* = \frac{\eta}{\psi(1-\epsilon)+\eta\epsilon} \in (0,1), \quad s_M^* = \frac{\eta\epsilon}{\psi(1-\epsilon)+\eta\epsilon} \in (0, s^*)$$

This is in contrast with the model of R&D investment by monopolists due to an exogenous technological advantage by Segerstrom (2007), which delivers the optimality of a negative R&D subsidy: this may show the importance of endogenizing monopoly persistence.

In conclusion, a model of Schumpeterian growth which incorporates some realistic features of the market for innovation like decreasing marginal productivity of investment, fixed costs and a first mover advantage for the incumbent monopolist, delivers realistic implications for the patterns of innovation. Market leaders invest a lot in R&D and their leadership is somewhat persistent, but sooner or later they are replaced by new entrants. This environment enhances innovation and growth.

5. Globalization and growth

In this section, I will extend the model to an open economy context with trade and capital flows to characterize the functioning of the market for innovations in a global setup[25]. The extension to a multicountry version is quite simple because of the absence of absolute scale effects. Actually, without trade frictions, the equilibrium growth in the global economy corresponds exactly to the one of the closed economy. When trade frictions exist, however, relative scale effects emerge: global growth is driven by innovations of firms in the largest country and it is enhanced by the relative size of this country, and by the degree of openness. Finally, I will evaluate R&D policy showing that governments may want to subsidize domestic firms for profit shifting reasons (as in the theory of strategic export promotion), while global efficiency requires international coordination of multiple instruments.

5.1. Schumpeterian growth in a multicountry model

Let us consider two or more countries endowed with the same technology and preferences as above, but different TFP and population levels. Labor does not move across countries and final goods freely move across borders, while there are frictions in trade of intermediates: imagine that for one unit of intermediate goods sent to a foreign country, $d \leqslant 1$ units arrive at destination because of iceberg transport costs or protectionism (but one may also think of losses due to incomplete protection of foreign IPRs): the parameter d can be interpreted as a measure of the degree of openness. These trade frictions imply that foreign demand is smaller than domestic demand for each intermediate good produced at home. In particular, the expected discounted value of the profits with innovation k_j by a firm from country i becomes:

$$V_i(\kappa_j) = \frac{\left(\frac{1-\theta}{\theta}\right)(\alpha\theta q^{\kappa_j\alpha})^{\frac{1}{1-\alpha}}\left[A_i^{\frac{1}{1-\alpha}}L_i + d^{\frac{1}{1-\alpha}}\sum_{f\neq i}A_f^{\frac{1}{1-\alpha}}L_f\right]}{r+p(\kappa_j)} \tag{29}$$

[25] See Grossman and Helpman (1991) on many related issues. See also Impullitti (2006a,b) for a related analysis.

which is a generalization of (9). When countries are homogeneous or market integration is perfect ($d = 1$), this value is the same everywhere and the allocation of R&D investment between firms of different countries is indeterminate. Otherwise, the value of innovations is higher for larger economies – meaning with larger values of $A_i^{\frac{1}{1-\alpha}} L_i$. As long as the productivity of the research efforts is the same in all countries, it is easy to verify that the endogenous allocation of R&D investment is always biased toward the largest country. More precisely, under Nash competition in the market for innovations, only its firms will invest in R&D, while under Stackelberg competition incumbent firms from other countries may keep investing and retain the leadership, but they will lose it sooner or later in favor of firms from the largest country. Therefore, for any initial allocation of the technological frontier, the engine of the world growth is in the largest economy, which gradually conquers the technological leadership in all innovative sectors[26].

The world economy must be characterized by a constant growth rate for all countries (differences would emerge reintroducing heterogeneity in TFP growth across countries). Growth increases in the relative size of the leading country, say $b = \max(L_f A_f^{1/(1-\alpha)}) / (\sum L_f A_f^{1/(1-\alpha)})$. For instance, consider Nash competition with $\epsilon \to 1$. The growth rate, as a function of the relative size of the leading country and of the degree of openness, becomes[27]:

$$g(d, b) = \frac{\left(\frac{1-\theta}{\theta\zeta}\right)\left[b + d^{\frac{1}{1-\alpha}}(1-b)\right] - \rho}{\gamma + (1-\alpha)/\alpha \ln q} \tag{30}$$

which boils down to the growth rate of the closed economy in case of perfect market integration ($d = 1$) or in case of a single country ($b = 1$)[28]. Even if this model does not exhibit absolute scale effects, as its closed economy version, "relative scale effects" emerge: the larger is the leading economy compared to the rest of the world, the higher is the growth rate: $\partial g / \partial b > 0$. A consequence of these relative scale effects is that the positive relation between openness and growth survives: $\partial g / \partial d > 0$. This is important because this relation is quite strong from an empirical point of view (see Barro and Sala-i-Martin, 2004 on the related evidence).

The equilibrium is characterized by intra-industry trade – as in Krugman (1980): even if the largest country has an absolute advantage in all sectors, it develops a comparative advantage in the intermediate goods sector. The clear consequence is that this country must export these intermediate goods and import final goods in the long run[29]. Finally, notice that the world interest rate has to equate world savings and investment, hence savings from all the world finance investments in the leading country. This may help explaining the Lucas paradox (Lucas, 1990) concerning why capital does not fly to poor countries, while often there is a flow of resources moving in the opposite direction. Summarizing, we have:

[26] Historically, a similar process realized during the XIX century with the Industrial Revolution in England and in the XX century when USA became first the largest world economy and then gradually conquered the technological leadership in most sectors; some observers would bet on China repeating this path during the XXI century.

[27] For consistency, now I assume: $\phi(\kappa_j) = [\zeta(\alpha q^{\kappa_j \alpha})^{1/(1-\alpha)} (\sum A_f^{1/(1-\alpha)} L_f)]^{-1}$.

[28] Related frameworks have been used in the literature on political geography and globalization – see Etro (2006c).

[29] At each point in time, the trade surplus in intermediate goods, national savings and net capital inflows will have to be matched by a deficit in trade of final goods and by investments.

Proposition 5. *In a open economy context with trade frictions, the largest country has a comparative advantage in the innovation sector and, in the long run, it leads alone the technological frontier, exports intermediate goods, imports final goods and attracts foreign capital to finance investment. Growth increases in the degree of openness and in the relative size of the largest country.*

Such an scenario may appear to extreme to be realistic, nevertheless, in a stylized way, it appears in line with the growth experience of the last decades. This was characterized by large R&D investments and high rate of technological progress in the US, by high US imports of final goods which allowed other countries to grow as well, exporting final goods to the US and importing American technology, and by impressive capital flows toward the US financing its large current account deficits and turning United States into the largest debtor country in the world.

5.2. R&D subsidies in the open economy

As in the closed economy model, also the decentralized international equilibrium derived above is dynamically inefficient and a system of R&D subsidies and entry fees would be welfare improving. However, countries have conflicting interests and the optimal R&D policy would not emerge in a decentralized way. Our model can be useful in assessing what would be the optimal unilateral R&D policy for a single country and what kind of coordination would be needed to achieve global efficiency.

For simplicity, consider the case of perfect market integration ($d = 1$), in which firms from any country can engage in R&D activity and equilibrium growth can be characterized exactly as in our closed economy model[30]. In such a case, the optimal R&D policy can be characterized exactly as in the closed economy. In particular, to restore efficiency in the market for innovations one should always subsidize firms, while optimal growth would require a system of R&D subsidies and entry subsidies or fees. However, it is difficult for a country to commit to permanent policies of this kind[31]. When a country decides a subsidy for a firm engaged in R&D activity in a particular market, the perceived impact on global growth is negligible, and the only rationale behind subsidization is profit shifting in favor of the same domestic firm (as in Brander and Spencer (1985)): however, this leads to inefficient unilateral policies.

In our framework, the problem of the optimal unilateral R&D policy is a particular case of a more general problem of optimal strategic export promotion investigated in Etro (2002, 2007). In particular, when the objective function of the subsidized domestic firm satisfies strategic complementarity, that is $\partial^2\Pi^i/\partial z_i\partial z_f > 0$, and marginal profitability increasing in the subsidy, that is $\partial^2\Pi^i/\partial z_i\partial s > 0$, we have the following: (1) when the number of competitors in the international competition is exogenous (as in the standard literature

[30] This is an immediate consequence of the lack of absolute scale effects.

[31] Imagine a situation where countries could commit to a permanent R&D subsidy. In our world without frictions, all countries would agree on what is the optimal policy. Nevertheless, each country would have an incentive not to subsidize R&D so as to "import" growth from foreign technological progress and enjoy more consumption. Moreover, the strategic interdependence of the policy tools is now more complex. In an interesting investigation, Impullitti (2006a,b) has examined a related model with two countries showing that R&D subsidies are strategic complements. He has also provided some numerical simulations for the Nash equilibrium subsidies and the optimal ones: his results suggests that the gains from R&D policy coordination can be quite large.

on strategic trade policy since Eaton and Grossman (1986)), there is always a unilateral incentive to tax R&D of the domestic firm, but (2) when entry in the international competition is endogenous, there is always a unilateral incentive to subsidize R&D of the domestic firm (and the result by Eaton and Grossman collapses)[32]. Here we are in the second case, and R&D subsidies are optimal because they provide the domestic firm with the incentive to invest aggressively in R&D, exactly as if this firm was a leader in the patent race. As a consequence, expected profits of the domestic firm (net of the subsidy) increase. In the Appendix B, I prove this result and derive the optimal unilateral R&D subsidy for any domestic firm as:

$$\hat{s} = \frac{\eta\theta(1-\epsilon)}{\left(\frac{1-\theta-\eta\theta}{1-\theta}\right)^{\frac{\epsilon}{1-\epsilon}}[(1-\theta)(1-\epsilon)+\epsilon\eta\theta]-\epsilon\eta\theta} \in (0,1) \tag{31}$$

Unfortunately, this policy just shifts profits from one country to another, crowding out investments by foreign firms in favor of the domestic subsidized firm[33], while aggregate growth is unaffected. In conclusion, we can summarize our findings as follows:

Proposition 6. *In an open economy context without trade frictions, the optimal unilateral policy for a single country is a positive R&D subsidy for the domestic firms active in the international market for innovations, but the optimal coordination of R&D policies requires both a positive R&D subsidy and an entry subsidy/fee as in the closed economy.*

Therefore, in the open economy context, independent R&D policies do not promote growth, which suggests a new and strong case for international cooperation of R&D policies[34]. As well, known, in the case of asymmetries between countries, for instance due to

[32] One can verify that here (in equilibrium) we have:

$$\frac{\partial^2 \pi^H}{\partial z_H \partial z_f} = \frac{\epsilon\phi(\kappa_j)^{\epsilon} z_H(\kappa_j)^{\epsilon-1}\mathbf{V}^M(\kappa_j+1)-(1-s_H)}{[r+p(\kappa_j)]^2} > 0$$

$$\frac{\partial^2 \pi^H}{\partial z_H \partial s} = \frac{r+p(\kappa_j)-\epsilon\phi(\kappa_j)^{\epsilon} z_H(\kappa_j)^{\epsilon}}{[r+p(\kappa_j)]^2} > 0$$

hence case 2 applies.

[33] A back of the envelope calculation under realistic calibration can help compare the optimal unilateral subsidy (31) with the subsidy chosen under optimal coordination, which corresponds to (17). Assume an optimal mark up of 10%, an elasticity of expected revenue to R&D investment $\epsilon = 0.5$, and imagine that fixed costs of investment are expected to be 10% of the profits in case of successful innovation, then the optimal unilateral subsidy on R&D is 11.2% which is below the optimal level 18.2%.

[34] Investments in R&D leading to global innovations are mainly concentrated in a few leading countries, that is United States, Japan and some European countries. US has been the technological leader in the last century, however, at the end of the 70s faced an erosion of its leadership and reacted in the early 80s introducing a Research & Experimentation Tax Credit, which was substantially an R&D subsidy for any (incremental) investment in technological R&D, launching a number of programs of direct funding for private research, strengthening IPRs protection for high-tech sectors and reducing antitrust prosecutions of joint ventures for pre-commercial research. Such a structural change in the R&D policy had a substantial impact in promoting investments (see Impullitti, 2006a,b), and between the 90s and the beginning of the XXI century, United States regained leadership in high-tech sectors, especially in the New Economy. While American investment in R&D has been historically around 2.5% of GDP in the last decades, investment is quite lower in Europe. Not by chance, one of the main objectives of the Lisbon agenda for the European Union is to increase R&D investment through subsidization and to coordinate such a policy across countries (see Katsoulakos et al., 2005). Nevertheless, R&D policies in Europe are still limited and ineffective.

trade frictions and heterogenous sizes, preferences on the optimal policies diverge and coordination becomes more problematic – see Alesina et al. (2005)[35].

6. Conclusions

In this work, I developed a model of creative destruction where the engine of growth is in the microeconomic structure of the patent races leading to innovations. In conclusion, I want to summarize the most substantial findings of this research from the point of view of the policy implications. Exploring a realistic organization of the market for innovations I found a new source of dynamic inefficiency of the growth process which is due to suboptimal investment by both incumbent patentholders and outside researchers and requires policies for the promotion of innovation (as R&D subsidies or higher protection of intellectual property rights) as a general remedy. In an open economy context, the need of similar policies and of their coordination is even stronger because single countries may tend to adopt policies that promote domestic firms, but do not enhance global investment in R&D.

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Appendix A. Optimal R&D policy for a closed economy

I derive the optimal organization of the R&D sector through an heuristic solution for the social planner problem. First of all, it is immediate to derive from the concavity of the arrival rate that it is optimal to allocate equal flows of investment between all the R&D laboratories. Consider linear investment flows in the future scale of production, as $z(\kappa_j) = \beta X(\kappa_j + 1) = \beta q^{\frac{\theta}{1-\theta}} X(\kappa_j)$ for each firm in sector j, where the parameter β must be chosen optimally. Let us keep the production of intermediates at the level chosen by the monopolist in the decentralized equilibrium. As well known, a social planner would not distort the choice of the input mix, hence we are basically solving for a second best allocation (the first best allocation would be obtained by subsidizing monopolists in such a way that their price equates marginal cost).

[35] Also in this framework, countries would like to subsidize their firms, but in different ways. The leading country could do it with the direct purpose of enhancing growth toward the efficient level. Other advanced countries could do it just to promote investment by their firms and conquer a leadership with the associated profits in some sectors (their optimal subsidy would also change with their relative size) without affecting the growth rate. Finally, less advanced countries could not even obtain advantages from subsidies. Once again, there would be a case for international coordination of R&D policies, but now heterogeneity between countries would create different incentives for different countries so as to complicate coordination. While a full analysis of world coordination is beyond the scope of this paper, we confirm the important result that when international growth is driven by endogenous technological progress there is a strong case for international R&D policy coordination.

The resource constraint of the economy must take into account the fixed costs, which are paid only at the beginning of each new patent race. Without loss of generality, let us assume that the economy devotes a flow of resources for this purpose in each sector. If the number of sectors N is high enough, one can approximate this flows, say $f_j(\kappa_j)$ with those equating their expected present value $f_j(\kappa_j)/[r + p(\kappa_j)]$ to the fixed cost $F(\kappa_j)$, that is with $f_j(\kappa_j) = \eta X(\kappa_j + 1)$. Using the expressions for the quantity of intermediate goods and for the output, we can rewrite the resource constraint as:

$$Y = \frac{X}{\alpha} = C + \sum_{j=1}^{N} X_j(\kappa_j) + \sum_{j=1}^{N}\sum_{i=1}^{n} z_i(\kappa_j) + \sum_{j=1}^{N}\sum_{i=1}^{n} f_j(\kappa_j) = \\ = C + X\left[1 + n(\beta+\eta)q^{\frac{\theta}{1-\theta}}\right] \tag{32}$$

from which we derive an expression for consumption holding at each point in time. Under the optimal allocation of resources, growth is determined by the rate of innovation as:

$$g = n\left[\phi(\kappa_j)z(\kappa_j)\right]^{\epsilon}\left[q^{\frac{\theta}{1-\theta}} - 1\right] \approx \left(\frac{\beta}{\bar{\zeta}}\right)^{\epsilon} \frac{\theta n \ln q}{1-\theta} \tag{33}$$

Given a constant growth rate of consumption, intertemporal utility is finite as long as $\rho > (1-\gamma)g$, and can be written as:

$$U = \int_0^{\infty} \frac{C_t^{1-\gamma}}{1-\gamma} e^{-\rho t} dt = \frac{C_0^{1-\gamma}}{(1-\gamma)[\rho - (1-\gamma)g]} \tag{34}$$

Finally, substituting (32) and (33) in (34), we can summarize the social planner problem as:

$$\max_{n,\beta} \frac{X_0^{1-\gamma}\left[\frac{1-\alpha}{\alpha} - n(\beta+\eta)q^{\frac{\theta}{1-\theta}}\right]^{1-\gamma}}{(1-\gamma)\left[\rho - (1-\gamma)\left(\frac{\beta}{\bar{\zeta}}\right)^{\epsilon}\frac{\theta n}{1-\theta}\ln q\right]} \tag{35}$$

If an interior solution exists, the first order conditions for the social planner problem (35) with respect to β and n can be used together to obtain $\beta^* = \epsilon\ \eta/(1\text{-}\epsilon)$, which implies the optimal flow of investment in R&D per firm (16) derived in the text. Let us now look at the number of firms investing in R&D. From the first order conditions we obtain the optimal number of R&D laboratories as:

$$n^* = \frac{\left[\left(\frac{1-\epsilon}{\eta}\right)\left(1 - q^{-\frac{\theta}{1-\theta}}\right)\left(\frac{1-\alpha}{\alpha}\right) - \rho\left(\frac{(1-\epsilon)\bar{\zeta}}{\epsilon\eta}\right)^{\epsilon}\right]}{\gamma\left[q^{\frac{\theta}{1-\theta}} - 1\right]} \tag{36}$$

which is decreasing in ϵ at least for ϵ high enough: this implies that when the marginal productivity of the investment is high enough, it is optimal to have just one laboratory investing in R&D. In what follows, we focus on the case where ϵ is small enough to guarantee the optimality of multiple laboratories. Substituting β^* and n^* in our expression for growth (33), we obtain that the optimal growth rate is:

$$g^* \approx \frac{1}{\gamma}\left[\left(\frac{\epsilon}{\bar{\zeta}}\right)^{\epsilon}\left(\frac{1-\epsilon}{\eta}\right)^{1-\epsilon}\frac{(1-\alpha)\theta\ln q}{\alpha(1-\theta+\theta\ln q)} - \rho\right] \tag{37}$$

which is higher than the equilibrium growth rate for any γ smaller than a cut-off (and tends to the Barro and Sala-i-Martin optimal growth rate approaching constant returns to scale, that is for $\epsilon \to 1$ and $\eta \to 0$).

To derive the optimal R&D policy let us introduce an entry fee which is the fraction τ of expected production costs in each patent race. The equilibrium growth rate becomes:

$$g(s,\tau) = \frac{\left[\frac{\epsilon(1-\theta-(\eta+\tau)\theta)}{\zeta(1-s)\theta}\right]^{\epsilon}\left[\frac{(1-\theta)(1-\epsilon)+\epsilon(\eta+\tau)\theta}{\eta\theta}\right]^{1-\epsilon} - \rho}{\gamma + (1-\alpha)/\alpha \ln q} \tag{38}$$

The optimal R&D policy is given by (s^*, τ^*) such that $z(k)$ and $g(s,\tau)$ equate $z^*(k_j)$ and g^*, that is:

$$s^* = \frac{1}{\left(\frac{1-\theta}{\eta+\tau^*}\right)\left(\frac{1-\epsilon}{\theta}\right) + \epsilon} \in (0,1) \tag{39}$$

$$\tau^* = \frac{\left[\left(\frac{1-\theta}{\theta}\right)(1-\epsilon) + (\eta+\tau^*)\epsilon\right]^{\frac{1}{1-\epsilon}}\left[\frac{\epsilon}{\zeta(1-\epsilon)}\right]^{\frac{\epsilon}{1-\epsilon}}}{[1+(1-\alpha)/\gamma\alpha\ln q]\gamma g^* + \rho} - \eta \tag{40}$$

which provide two unique optimal policy tools. Clearly $g^* < g(s,0)$ for γ high enough, in which case, the optimal entry fee is positive.

Appendix B. Optimal unilateral R&D policy for a small open economy

Consider the decentralized equilibrium with Nash competition in the market for innovations, but imagine that country H can choose an R&D subsidy s_H to promote its own single firm in the international competition for innovation κ_j for some sector j. The expected profits of its domestic firms active in sector j are:

$$\pi^H(\kappa_j, s_H) = \frac{[\phi(\kappa_j)z_H(\kappa_j)]^{\epsilon}\mathbf{V}^M(\kappa_j+1) - (1-s_H)z_H(\kappa_j)}{r+p(\kappa_j)} - F(\kappa_j) \tag{41}$$

Whether country H subsidizes or not its firm, the aggregate variables like the growth rate and the world technological progress will not be affected, therefore, the only reason for which country H may want to subsidize its firm is profit shifting. As usual in the theory of strategic trade policy, a country may undertake unilateral export promoting policies to increase net welfare in terms of expected profits net of the expected cost of the subsidies:

$$W(s_H) = \pi^H(\kappa_j, s_H) - \frac{s_H z_H(\kappa_j)}{r+p(\kappa_j)} \tag{42}$$

To focus on the problem of the optimal unilateral subsidy, suppose that subsidies are zero for all the other countries. The equilibrium is fully characterized by the first order conditions for the optimal investments $z_H(\kappa_j)$ for the domestic subsidized firm and $z(\kappa_j)$ for the foreign unsubsidized firms, and by the free entry condition which pins down the number of active foreign firms. The last two conditions are the same as before, namely:

$$z(\kappa_j) = \epsilon^{\frac{1}{1-\epsilon}}\phi(\kappa_j)^{\frac{\epsilon}{1-\epsilon}}[V(\kappa_j+1) - F(\kappa_j)])^{\frac{1}{1-\epsilon}}$$

and

$$\frac{[\phi(\kappa_j)z(\kappa_j)]^{\epsilon}V(\kappa_j+1)-z(\kappa_j)}{p(\kappa_j)+r}=F(\kappa_j)$$

The first order condition for the domestic subsidized firm is:

$$\begin{aligned}&[\epsilon\phi(\kappa_j)^{\epsilon}z_H(\kappa_j)^{\epsilon-1}\mathbf{V}^M(\kappa_j+1)-1+s_H][r+p(\kappa_j)]\\&\quad=\epsilon\phi(\kappa_j)^{\epsilon}z_H(\kappa_j)^{\epsilon-1}\{[\phi(\kappa_j)z_H(\kappa_j)]^{\epsilon}\mathbf{V}^M(\kappa_j+1)-(1-s_H)z_H(\kappa_j)\}\end{aligned}$$

This system of three equations provides investment by foreign firms $z(\kappa_j)$ and aggregate probability of innovation $p(\kappa_j)$ independently from the domestic subsidy, while the investment of the domestic firm, $z_H(\kappa_j, s_H)$, is increasing in the subsidy (and the number of foreign entrants is decreasing in it). This implies that we can rewrite domestic welfare as:

$$W(s_H)=\frac{[\phi(\kappa_j)z_H(\kappa_j,s_H)]^{\epsilon}\mathbf{V}^M(\kappa_j+1)-z_H(\kappa_j,s_H)}{r+p(\kappa_j)}-F(\kappa_j) \tag{43}$$

which is maximized as long as the optimal subsidy s_H^* satisfies the first order condition:

$$\epsilon\phi(\kappa_j)^{\epsilon}z_H(\kappa_j,s_H^*)^{\epsilon-1}\mathbf{V}^M(\kappa_j+1)=1 \tag{44}$$

The resulting investments:

$$z(\kappa_j)=\frac{\{\epsilon\phi(\kappa_j)[\mathbf{V}^M(\kappa_j+1)-F(\kappa_j)]\}^{\frac{1}{1-\epsilon}}}{\phi(\kappa_j)}<z_H(\kappa_j,s_H^*)=\frac{[\epsilon\phi(\kappa_j)\mathbf{V}^M(\kappa_j+1)]^{\frac{1}{1-\epsilon}}}{\phi(\kappa_j)}$$

show that the government subsidy puts the domestic firm in the position of a Stackelberg leader in its patent race, a well known result in the theory of strategic trade policy. Nevertheless, as long as the R&D subsidies are just provided for the single patent race and not for the future ones, the value any innovation is not affected and the equilibrium aggregate variables are unchanged compared to the basic decentralized equilibrium.

Substituting the implicit expression for the optimal subsidy (44) in the equilibrium system we can implicitly derive the optimal subsidy as:

$$s_H^*=\left[1+\frac{[r+p(\kappa_j)-[\phi(\kappa_j)z_H(\kappa_j)]^{\epsilon}]\mathbf{V}^M(\kappa_j+1)}{[\phi(\kappa_j)z_H(\kappa_j)]^{\epsilon}\mathbf{V}^M(\kappa_j+1)-z_H(\kappa_j)}\right]^{-1}\in(0,1) \tag{45}$$

Finally, adopting our assumptions on the functional forms, we can explicitly obtain the optimal unilateral R&D subsidy for any domestic firm in the text[36].

The natural question one may ask at the end of this discussion is whether a Nash equilibrium with positive symmetric subsidies can emerge when all countries can choose their

[36] Clearly, if a government could commit to subsidize forever R&D investors including firms that achieved the world leadership, the value of innovating for a domestic firm would be above the corresponding value for a foreign firm, which could induce endogenous investment by the domestic patentholder in a way similar to the case with a first mover advantage for the latter. A commitment to permanent R&D subsidization could then enhance growth and the optimal policy would then be chosen to maximize domestic welfare: clearly in our model this would be a prosper-thy-neighbor policy. However, in a long term perspective we should also take in consideration that in front of a permanent subsidization policy, new domestic firms would endogenously enter in the market for innovations. Such an entry process would end only when these firms would be earning zero profits. Notice that in such a case, any profit shifting rationale behind R&D subsidization would be lost.

R&D policy in a decentralized way. This is what happens in standard models of strategic trade policy with imperfect competition, where the Nash equilibrium is inefficient compared to the cooperative solution[37].

Consider the simplest situation in which only a single patent race is under consideration. First of all, it is easy to verify that the optimal subsidies are strategic substitutes in this model (one can rework the derivation of the optimal R&D subsidy when the other countries adopt a common subsidy s and verify that $\partial s_H^*(s)/\partial s < 0$): the intuition is that foreign R&D subsidization reduces the gains from domestic investment. Nevertheless, it is also easy to verify that under international free entry a symmetric equilibrium where all countries adopt the same subsidy becomes unfeasible: if this was the case, all firms would expect the same zero profits and the subsidization policies would just have a cost without a benefit[38].

While asymmetric equilibria with some countries subsidizing their firms (and other countries not doing it) could exist, their characterization is beyond the scope of this discussion. What matters here is that, even in such a case, any equilibrium must be characterized by the free entry condition holding on firms without subsidies. Once again, this implies that any R&D policy (by any of the other countries) would not affect aggregate growth.

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[37] Notice that in the standard static literature on export subsidies (as in Brander and Spencer, 1985) the Nash equilibrium implies excessive subsidization (since the optimal cooperative policy requires export taxes).

[38] Formally, in the plane (s, s_H^*) there is not a symmetric equilibrium with $s_H^*(s) = s$ because the best response function has a discontinuity (it jumps to $s_H^*(s) = 0$ for any $s > \hat{s}$ with $s_H^*(\hat{s}) > \hat{s}$).

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