Science-Based R&D in Schumpeterian Growth

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Abstract

Firm success is often associated with the development of better products. Private firms undertake applied R&D seeking market advantage, by capitalizing on the freely accessible results of basic research. But unpatentable basic research often fails to address applied R&D open problems. What is the role of the incentives in improving the innovative performance of an economy by matching partially motivated public researchers to their mission? Sometimes government funded research projects are mission-directed, yet in many cases the public sector academics indulge in carrier-driven research. An innovation system where, as in the US, also basic research is driven by patents, implicitly sets an *ex-post* incentive to the researchers guided by invisible hand. For a public innovation system - like the European one - designing an incentive scheme to motivate public researchers is of key importance for fostering the performance of the economic system. This paper extends the Schumpeterian multisector growth model with vertical innovation by highlighting a link between the degree of "targetness" of public research and aggregate innovation. A positive effect of social capital is also proved. *Keywords*: Sequential Innovation, Research Tools, Basic Research, Knowledge Management, Social Capital. *JEL Classification*: H44, O31, O34, O38.

1 Introduction

We are in a period of fundamental reconsideration of US science and technology policy. The end of the Cold War, the changing nature of US economic competitiveness, and the increasing direct involvement of the Congress in science policy have led to a lack of stability in goals and philosophy. The roles of government, industry, and academia are being examined in a fundamental way.

Charles West, President of MIT, MIT 1995 p.2.

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Through the creation of a patent system, policy makers always tried to create a protected ideal place for the creation and the transmission of a public good - new knowledge and technology. Governments assign to the patent systems the main functions of incentivizing the production of new technologies, of informing society about their availability, and of creating a market for such new technologies. When this regulated market works properly - even at the cost of creating some additional distortions - then consumers enjoy the benefits of the resulting innovative output produced in the economy. In this sense, it has often been stressed how, among the different instrument for protecting intellectual property, patents constitute the most market-oriented ones (Guellec, 2007). Besides the two functions traditionally assigned to the patent system - incentivizing and diffusing innovations in the economy - stands out a third political task: orienting R&D activity towards the consumers' needs[1]. We will focus on this in our paper, with special attention to the non-patentable aspects of research.

Several studies - echoed by frequent industry leaders' complaints - point out an increasing complexity in the applied R&D activity (Kortum, 1993 and 1997; Segerstrom, 1998). If applied R&D - i.e. the private innovative arena - is becoming increasingly more complicated, it may be crucial from a social point of view to develop solid instruments of technological transfer from basic research. Of course, a more and more difficult applied research also reveals a closer and closer interconnectedness between applied and basic research: to produce new medical treatment, it is crucial to have an improvement in the basic understanding of the pathologies. A good ongoing interaction between basic and applied R&D, therefore implies that the scientists' awareness of the importance of the allocation of their basic research efforts between the changing open questions of applied science and technology could play a central role in promoting progress.

A lot of basic research is public, particularly so in Europe and Asia, less so in the US after the beginning of the Eighties. The efficient provision of public services, in the case publicly driven R&D, necessarily means the ability of a government-led public innovation system to generate more innovations well targeted from the society point of view . Hence the need to theoretically explore the dimension of applied vs fundamental R&D in a macroeconomic framework. In this paper, we develop a variant of Cozzi and Galli (2008) R&D-driven growth model, with the explicit aim of analyzing the effects on equilibrium innovation of simple monetary and non-monetary incentive schemes to the basic researcher in the public system, when basic research outcomes are not patentable.

The structure of the model presented here, as in Cozzi and Galli (2008), envisages basic and applied R&D in all sectors of the economy. Within each industry, firms are distinguished by the quality of the final good they produce. When the state-of-the-art quality product in an industry $\omega \in [0, 1]$ is $j_t(\omega)$, research firms compete in order to learn how to produce the $j_t(\omega) + 1$st quality product. This learning process involves a two-stage innovation path, so first a

[1] This is the utilitarian approach to the economics of science-based innovation: to ask if and in what extent publicly employed scientists provide their customers (i.e. all the consumers) with more or less satisfactory answers to their real needs.

R&D unit catches a glimpse of innovation through the $j_t(\omega) + \frac{1}{2}$th inventive half-idea and then other firms engage in a patent race to implement it in the $j_t(\omega) + 1$st quality product. We rule out basic research secrecy and assume that, once invented, the first "half-idea" can be used by anyone who wants to try to complete it. Also, we assume that "half-ideas" are industry specific. A more general analysis, to be done in future works, should also include new general purpose technologies.

In our model, only non-profit motivated R&D units - i.e. public laboratories - try to invent a new first half idea in the basic research sector. We assume that R&D firms are able to instantaneously patent only the complete idea of a product innovation. Then, patent protection may determine a monopolistic position in the final good sector, and the winner of the final patent R&D race becomes the sole producer of a $j_t(\omega) + 1$ quality consumption good.

Unlike Cozzi and Galli (2008), where public basic research workers did not care about the potential industrial applicability of their findings, we here adopt a more optimistic view of the public sector: we will assume that the government prizes researchers who more than others discover potentially useful scientific findings. This entails a race to target basic research where there are better chances of finding an industrial application. However, since basic researchers know that the government has only imperfect information about the usefulness of their discoveries, they will purposefully undertake research also in other subfields, where they have better chances to win the race. This entails a distribution of efforts in both useful and useless fields.

The same incentive scheme can be interpreted as modelling non-monetary compensations to above average researchers, in which status is granted by the academic community. Then we prove that the higher "social capital", the more closely observed the scientist's effort by their peers, thereby leading to more targeted innovation. Social capital, paired with socially responsible social norms, can induce more innovation in equilibrium, as we will prove. Hence both monetary and non-monetary compensations can have an effect, in a patent-free open science world.

The paper is organized as follows. Section 2 surveys - inevitably incompletely - the literature on innovation and growth relevant for our model. Section 3 lays down the model. Section 4 studies the equilibrium and derives the main results. Section 5 concludes with some comments.

2 Related Literature

Starting in the early Nineties two main strands of literature, both aimed at exploring the linkages between R&D, intellectual property and the economic performance, developed. Probably motivated by the U.S.A. loss in technological competitiveness (compared to Europe and Japan) during the Eighties, these two flows tried to incorporate the logic of the patent race literature first invented during the Eighties (see, among the others, Fudenberg et al. (1983), Reinganum (1985), Grossman and Shapiro, (1987) into two new class of models.

One adopted a dynamic general equilibrium approach in order to depict the effects on economic growth of the alternance in time of different monopolistic positions producing (and selling) on the market only the top-quality existing good or service in a given production line, each of these monopolistic positions being the result of an endogenous choice to invest in R&D by private entrepreneurs. This was the R&D-driven growth theory - among many other contributions see Segerstrom, Anant and Dinopolous (1990), Romer (1990), Aghion and Howitt (1992) and (1996), Grossman and Helpman (1991).

Schumpeterian growth theory did not miss to acknowledge the importance of accounting for the sequential and cumulative nature of ideas, by identifying basic research with horizontal innovation (Aghion and Howitt, 1996), by merging the patent-design literature and the endogenous growth literature in a general equilibrium framework (O'Donoghue and Zweimuller, 2004). In a similar vein, it explicitly considers the possibility for an idea at pre-commercial stages of development, or for an essential part of it, to be appropriated by non-inventors (Cozzi, 2001; Cozzi and Spinesi, 2006).

The second stream of literature, by focussing on the problem of rewarding R&D activity within the framework of sequential innovation, initially dominated the discussion on intellectual property. After the pioneering contributions of Grossman and Shapiro (1987), Scotchmer (1991), O'Donoghue, Scotchmer and Thisse (1994), a broad literature[2] now recognized that "*most innovators stand on shoulders of giants*"[3], i.e. innovation is a process sequential and cumulative in nature where each invention builds on previous ideas. The biotechnology sector offers many illustrations of the sub-sequential behavior of the research activity. For example, success in advanced biotechnology, in agricultural, and medical applications fields is made possible thanks to the progress in genetic engineering allowing to transfer genetic sequences from one organism to another.

Moreover, for some fundamental basic ideas applications can be nothing but indirect (Guellec, 2007). This is the case of the research tools which bear no direct improvements in the consumer's utility, but they serve to develop future marketable innovative products (Cozzi and Galli, 2008). The debate on the patentability of the research tools specially warmed up with reference of the ability of basic research to spawn marketable developments. Merger and Nelson (1990) emphasized the importance of considering the economic significance of patents from the perspective of their scope. These authors (see also Heller and Eisenberg, 1998) argued that, particularly in the most innovative industries, fundamental patents are often overbroad and this is likely to slow down follow-on research and warned against an excessive commercialization of scientific advances reached by public R&D: *"A science-based industry straddles the public world of science and private world of intellectual property; an overbroad patent makes private part of the public science such an industry strives to*

[2] Scotchmer (2004) and Hopenhayn, Llobet and Mitchell (2006) provide two recent optimal surveys on the literature.

[3] Scotchmer, (1991).

commercialize"[4].

Aghion, Dewatripont and Stein's (2008) model analysis multi-stage discovery processes in R&D activity where the allocation of intellectual property rights is crucial for the promotion of knowledge production and innovation. In particular, in the comparison between free and private research, they find that in early stages of the innovation process it is optimal to opt for a public innovation system, able to better guarantee the researcher's freedom respect to private-sector research which, by contrast, becomes optimal in the later stages of the discovery process.

The possibility of a "neck-to-neck" competition between current technological leaders and their followers in an industry was first introduced by Aghion, Harris and Vickers's (1997) model and later developed by Aghion, Harris, Howitt and Vickers (2001). In these models innovations by leaders and followers occur step-by-step. Unlike the majority of R&D-driven growth models where all innovations are made by outsider firms[5], Aghion, Harris and Vickers (1997) provide a powerful analytical structure able to make innovation incentives depend not so much upon post-innovation expected monopoly rents, but upon the expected difference between the post-innovation and the pre-innovation monopoly rents of the incumbents[6].

O'Donoghue (1997), O'Donoghue and Zweimuller's (2004), and Hunt (2004 and 2006) are particularly interesting in that they identify a role for patents in providing protection against future innovators: patentability requirement and leading breadth are able to affect the characteristics of new products, or the types of cost reduction that firms pursue, and could compensate the tendencies of suboptimally small innovations.

Unlike Aghion and Howitt (1996), Cozzi and Galli's (2008) analysis assumes that in each sector of the economy the innovation process can be split into two stages: basic research and applied research. The authors build a model to analyze the behavior of the public sector under different intellectual property regimes; calibrate the model to the US data; and punctually estimate the basic and applied research productivity from 1975 to 1981. The two model-structures just depicted - Aghion and Howitt (1996) and Cozzi and Galli (2008) - appear to be quite complementary since they are best suited to address the different concerns present in the literature about the desirability of reforming the patent system. In particular, Aghion and Howitt's (1996) model seems more appropriate for exploring the effect of enhancing patent protection in a contest in which - according some authors like Merger and Nelson (1990) - the most innovative industries are those of most recent creation, like the biotechnological. Cozzi and Galli's (2008) approach applies fairly well to the conception, pioneered by Nelson and Rosenberg, of a basic academic investigation and applied R&D as mutually

[4] Merges and Nelson, (1990).

[5] Cozzi (2007) proved that, when R&D is perfectly competitive, this is not a necessary implication of the Arrow effect.

[6] For a theoretical integration of the "neck-to-neck" competition approach with the analysis of the welfare-maximizing IPR policy see Acemoglu and Akcigit (2008).

feeding activities[7], emphasizing that "*the traditional distinction between "basic" and "applied" science are anachronisms*[8]".

Finally, important contributions try to analyze the allocation of property rights in the contest of heterogeneous R&D activity, by merging the literature on R&D organization, optimal allocation of intellectual property rights and the incomplete contract theory, developed by Grossman and Hart (1986) and Hart and Moore (1990). Two influential examples of this literature on the allocation of property right are Aghion and Tirole (2004a and 2004b)'s articles. In these models two separate entities - a research unit and a customer- are involved into two simultaneous but operatively distinct stages of the innovation process: research and development (or commercialization). The division on the property rights across the two entities determines the incentive to supply their respective efforts.

However, it was after the pioneering microeconomic contributions of Fudenberg et al. (1983), Reinganum (1985), Grossman and Shapiro (1987) and Green and Scotchmer (1995) that economists had become aware of the strategic dimension of sequential research activity. The possibility that in the real world innovators may use the patents they hold just to block future innovators (Bessen and Maskin, 2009), and/or prevent them from commercializing their products raised a still increasing concern[9] not only among academics.

3 The Model

This section sets up a Schumpeterian model with sequential innovation where basic research findings are conceived and put into the public domain, and subsequently embodied into marketable products by a large number of perfectly competitive private R&D firms. This builds on a simplified version of Cozzi and Galli's (2008) section on unpatentable research tools. Unlike that paper, we are able to introduce a richer view of the public research sector, as well as obtain analytical results.

[7]"Medical scientists still lack understanding of just why and how certain effective pharmaceuticals do their work, and theories about that change from time to time. Much of engineering design practice involves solutions to problems that professional engineers have learned "work", without any particularly deep understanding of why........Thus, the discovery by Shockley and his team at Bell Laboratories that a semiconductor device they had built as an amplifier worked, but not in the way they had predicted, led him to understand that there was something wrong, or incomplete, about the theory in physics regarding the electrical characteristics of semiconductors, which in turn led to his own theoretical work, and a Nobel Prize. A non-trivial amount of research in the biomedical sciences is aimed at understanding better why the human body responds, or doesn't respond, to particular substances (including pharmaceuticals) the way it does. ... a number of most challenging puzzles science has had to face have been made visible by or been created by new technologies, and the puzzles of why they worked as they did." (Nelson, 2006: p. 7-8).

[8]Rosemberg and Nelson (1996, p.91).

[9]Heller and Eisenberg (1998) suggested the existence of a *tragedy of the anticommons*, i.e. a proliferation of upstream intellectual property rights which greatly amplify the transaction cost of downstream R&D, thus hampering downstream research for biomedical advance.

Time is continuous with an unbounded horizon and there is a continuum of infinitely-lived dynasties with identical intertemporally additive preferences. Heterogeneous labour, skilled and unskilled, is the only factor of production. Both labour markets are assumed perfectly competitive. In the final good sectors $\omega \in [0,1]$ monopolistically competitive firms produce differentiated consumption goods by employing unskilled labour, whereas research firms employ skilled labour.

3.1 Households

A each time $t \geq 0$ population is constant and normalized to 1. The representative household's preferences are represented by the following intertemporal utility function:

$$U = \int_0^{\infty} e^{-\rho t} u(t)\, dt, \tag{1}$$

where $\rho > 0$ is the subjective discount rate, and $u(t)$ is the instantaneous utility of each family member, and it is defined by:

$$u(t) = \int_0^1 \ln \left[\sum_j \gamma^j d_{jt}(\omega) \right] d\omega, \tag{2}$$

where $d_{jt}(\omega)$ is the per family member consumption of a good $\omega \in [0,1]$ of quality j (that is, a product that underwent $j = 0, 1, 2, ...$ quality jumps) at time t. This formulation, the same as Grossman and Helpman (1991), assumes that each consumer prefers higher quality products. In particular, parameter $\gamma > 1$ measures the size of the quality upgrades (i.e., the magnitude of product innovations).

The representative consumer is endowed with $L > 0$ units of skilled labor and $M > 0$ units of unskilled labor summing to 1. Since labour bears no disutility it will be inelastically supplied for any level of non negative wages. Since population is normalized to 1, L and M will also equal, in equilibrium, the per-capita supply of skilled, respectively, unskilled labour. Unskilled labor can only be employed in the final goods production. Skilled labour can only perform R&D activities.

In the first step of the consumer's dynamic maximization problem, she selects the set $J_t(\omega)$ of the existing quality levels with the lowest quality-adjusted prices. Then, at each instant, the households allocate their income to maximize the instantaneous utility (2) taking product prices as given in the following static (instantaneous) constraint equation:

$$E(t) = \int_0^1 \sum_{j \in J_t(\omega)} p_{jt}(\omega) d_{jt}(\omega)\, d\omega. \tag{3}$$

Here $E(t)$ denotes per-capita consumption expenditure and $p_{jt}(\omega)$ is the price of a product of quality j produced in industry ω at time t. Let us define

$j_t^*(\omega) \equiv \max\{j : j \in J_t(\omega)\}$ Using the instantaneous optimization results, we can re-write (2) as

$$
\begin{aligned}
u(t) &= \int_0^1 \ln\left[\gamma^{j_t^*(\omega)} E(t)/p_{j_t^*(\omega)}(\omega)\right] d\omega = && (4) \\
&= \ln[E(t)] + \ln(\gamma) \int_0^1 j_t^*(\omega) d\omega - \int_0^1 \ln[p_{j_t^*(\omega)}(\omega)] d\omega && (5)
\end{aligned}
$$

The solution to this maximization problem yields the static demand function:

$$
d_{jt}(\omega) = \begin{cases} E(t)/p_{jt}(\omega) \text{ for } j = j_t^*(\omega) \\ 0 \text{ otherwise.} \end{cases} \tag{6}
$$

Only the good with the lowest quality-adjusted price is consumed, since there is no demand for any other good. We also assume, as usual, that if two products have the same quality-adjusted price, consumers will buy the higher quality product - although they are formally indifferent between the two products - because the quality leader can always slightly lower the price of its product and drive the rivals out of the market.

Therefore, given the independent and - in equilibrium and by the law of large number - deterministic evolution of the quality jumps and prices, the consumer will only choose the piecewise continuous expenditure trajectory, $E(\cdot)$, that maximizes the following functional

$$
U = \int_0^\infty e^{-\rho t} \ln[E(t)] dt. \tag{7}
$$

Assume that all consumers possess equal shares of all firms at time $t = 0$. Letting $A(0)$ denote the present value of human capital plus the present value of asset holdings of the family at $t = 0$, each household's intertemporal budget constraint is:

$$
\int_0^\infty e^{-R(t)} E(t) dt \leqq A(0) \tag{8}
$$

where $R(t) = \int_0^t r(s) ds$ represents the equilibrium cumulative real interest rate up to time t.

Finally, the representative consumer chooses the time pattern of consumption expenditure to maximize (7) subject to the intertemporal budget constraint (8). The optimal expenditure trajectory satisfies the Euler equation:

$$
\dot{E}(t)/E(t) = r(t) - \rho \tag{9}
$$

where $r(t) = \dot{R}(t)$ is the instantaneous market interest rate at time t.

Euler equation (9) implies that a constant (steady state) per-capita consumption expenditure is optimal when the instantaneous market interest rate equals the consumer's subjective discount rate. Since preferences are homothetic, in each industry aggregate demand is proportional to the representative consumer's one. E denotes the aggregate consumption spending and d denotes the aggregate demand.

3.2 Manufacturing

In this section we examine the production side of the economy. We assume constant returns to scale technologies in the (differentiated) manufacturing sectors represented by the following production functions:

$$y(\omega) = M(\omega), \text{ for all } \omega \in [0,1], \tag{10}$$

where $\alpha \in (0,1)$, $y(\omega)$ is the output flow per unit time, and $M(\omega)$ is the skilled labour employment in industry $\omega \in [0,1]$. Full employment and symmetry imply that in equilibrium: $M(\omega) = M$.

In each industry, at each instant, firms compete *a la* Bertrand. Given demand function (6), within each industry product innovation is non-drastic, hence the quality leader will fix its (limit) price by charging a mark-up γ over the unit cost (remember that parameter γ measures the size of product quality jumps).

$$p_{j_t^*(\omega)}(\omega) = \gamma \Rightarrow d = \frac{E}{\gamma}. \tag{11}$$

Hence each monopolist earns a flow of profit, in per-capita terms, equal to

$$\pi = (\gamma - 1) M = \frac{\gamma - 1}{\gamma} E. \tag{12}$$

Since M is constant, also $E(t) = \gamma M$ will be constant. Therefore, by the Euler equation (9) the real interest rate will be constant:

$$r(t) = \rho. \tag{13}$$

3.3 R&D Sectors

Traditionally, the European institutional organization of science-based research has been similar to a pre-1980 US innovative environment. In order to emphasize the role of publicly hired researchers' attitude towards more directly marketable discoveries here we assume a normative framework in which the patent protection of the basic R&D results cannot be awarded.

We assume that R&D is a two-stage process in continuous time: first a "half idea" - or "research tool" - is invented by basic researchers, and then a final product is invented by applied researchers building on the latest half idea. Hence, after a "half idea" has arrived in an industry that lacked it, no more research tools are needed in that industry until the next turn of product improvement. Any new basic research result would be "redundant": maybe useful for the researcher's *CV* or reputation as a smart scientist, but not for the profit seeking downstream firms. As a result, at any time t, the whole set of industries $[0,1]$ gets partitioned into two sets of industries: industries $\omega \in A_0$ (temporarily) with no half-ideas and, therefore, with one manufacturing quality leader (the final product patent holder) indirectly challenged by the public R&D units; and the industries $\omega \in A_1 = [0,1] \setminus A_0$, with one half-idea and, therefore, one manufacturing leader (the final product patent holder) and a mass of private R&D firms aiming to complete the half-idea and to displace the current monopolist. These sets[10] keep changing over time as a result of the ongoing two-stage R&D processes. We assume that along each equilibrium the sets A_1 and A_0 are measurable at all dates. Researchers can engage in useful basic R&D only in $\omega \in A_0$ industries and they can engage in applied R&D activity aimed at a direct product innovation only in A_1 industries. When a quality improvement occurs in an A_1 industry the R&D firm that completed a half-idea becomes the new quality leader and the industry no longer belongs to A_1, but to A_0. When a half-idea discovery arises in an industry $\omega \in A_0$ this industry is no longer an element of A_0, but becomes an element of A_1 and the second-stage downstream patent race starts. Notice that the two sets A_0 and A_1 change over time, even if the economy is at a steady state. Figure 1, taken from Cozzi and Galli (2008), illustrates this industrial dynamics.

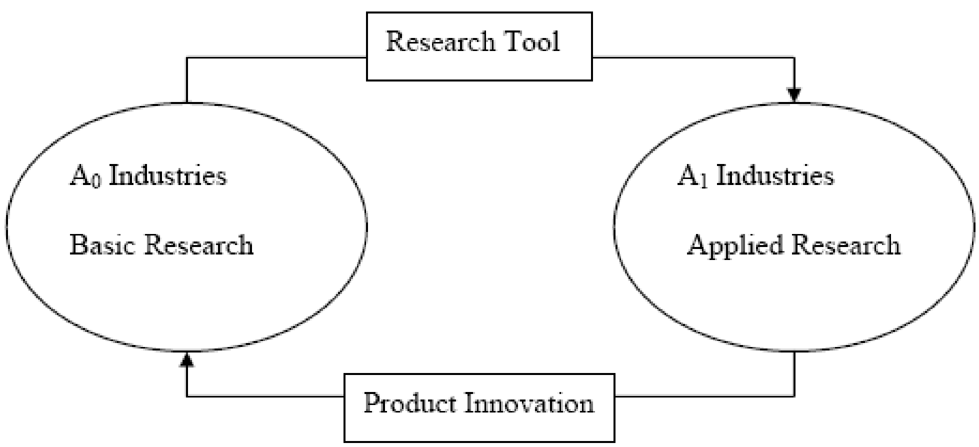

FIGURE 1: REPRESENTATION OF THE ECONOMY BY FLOWS OF INDUSTRIES

At any instant we can measure the mass of industries without any half-idea as $m(A_0) \in [0,1]$, and the mass of industries with an uncompleted half-idea as $m(A_1) = 1 - m(A_0)$. Clearly, in a steady state these measures will be constant, as the flows in and out will offset each other, whereas off steady state they might be changing. We assume that in all equilibria $m(A_0)$ and $m(A_1)$ are differentiable functions of time. All innovation processes follow independent Poisson processes, whose intensities are soon to be described.

Let $n_B(\omega, t)$ denote the mass of skilled labour employed in public universities and undertaking basic R&D in industry $\omega \in [0,1]$; and let $n_A(\omega, t)$ denote the

[10] Better written as $A_0(t)$ and $A_1(t)$: we drop time indexes only to keep notation simpler.

mass of skilled labour employed by freely entrant R&D firms[11] and undertaking applied R&D in industry $\omega \in A_1$. Each unit of basic research labour faces probability $\lambda_0 n_B^{-a}(\omega, t)$ per unit time of discovering a new result in industry $\omega \in [0, 1]$, where $\lambda_0 > 0$. This implies that also redundant basic research results can be invented. Each unit of applied research labour can invent a new product in an industry[12] $\omega \in A_1$ with probability intensity $\lambda_1 n_A^{-a}(\omega, t)$, where $\lambda_1 > 0$. Parameter $a > 0$ is an inter-industry congestion parameter, capturing the risk of R&D duplications, knowledge theft and other diseconomies of fragmentation in the R&D.

The government exogenously sets a constant fraction, $\bar{L}_G \in [0, L]$, of population of skilled workers to be allocated to the basic research activities conducted by universities and other scientific institutions. Moreover, basic R&D expenditure, equal to $\bar{L}_G w_s(t)$, is funded by lump sum taxes on consumers. The assumption of lump sum taxation guarantees that government R&D expenditure does not imply additional distortions on private decisions. This allows us to use the previous notation and derivations also for the case of a balanced government budget taxing all households in order to transfer the tax proceeds to the basic R&D workers.

3.3.1 Public Research Incentives

We could have made the following behavioral rule for public researchers: being public researchers perfectly mobile across sectors, when in a sector ω that lacked a half-idea, i.e. belonged to A_0, a half-idea appears, i.e. it becomes an element of A_1, the public R&D workers stop carrying out basic research in that sector and find the closest basic research problem only in the new A_0 set of sectors. This would be optimal from a social point of view. This may represent the case of university researchers who keep investigating open trajectories only when they know that private R&D firms will later profit from adapting to their market the new knowledge they may create. Unguided by the invisible hand, researchers may follow it indirectly, motivated by perfect altruism towards society: depending on their social motivation they will choose to become more or less intellectually mobile.

Notice that in our stylized economy final product patents are the main source of profits. Therefore, the "altruistic" scientist knows he/she is helping, for free, private firms to make potentially huge profits. Hence, pure envy could frustrate altruism, particularly so if public academics share an anti-profit view of science.

[11] Obviously, they could be private or public. In so far as even universities have "privatized" divisions, they could pursue profit as well. None of these considerations about the firm ownership change the results, though of course they could change the real world interpretation and the discussion about the realism of this model in the face of actual data.

[12] If we admit also the possibility of inventing redundant "me too" final products, in $\omega \in A_0$, we will assume that the patent office will never grant a patent on it, thereby killing the incentive to develop it. This is why there is no loss of generality in excluding them from the start. Instead, offering a probability of the patent office's protecting them would generate an interesting extension, joining our model with Segerstrom's (1991) pioneering contribution on Schumpeterian imitation.

The final good monopolists - the final patent owners - will also be periodically criticized for producing less than what perfectly competitive firms would in a patent free world: this could discourage "altruistic" scientists and make them retreat in an ivory tower, just to avoid participating in a game they do not like[13]. Therefore the difficulty in disentagling "altruism" towards consumer needs from "altruism" towards rich capitalists profiting from temporary monopolies is as old as the patent system.

Hence, somewhat more realistically, we assume that individual "altruism" is negligeable, and pecuniary and status seeking incentives take the lead. In this paper, we imagine that the public sector tries to induce more attention to consumer needs by prizing (respectively, penalizing) the basic researchers - in excess of the usual skilled wage income, w_s - based on how strongly they outperform (respectively, underperform) their colleagues. Let the prize per unit of excess discovery be κ. If the researcher is inventing a redundant research tool (i.e. a research tool in a sector $\omega \in A_1$), the prize will not be granted with probability p, while he/she will be prized anyway with probability $1-p$. Redundant discoveries detection probability p is less than 1 due to screening problems. Letting $y_i(t)$ denote the expected income flow of public researcher i targeting sector ω, at time t, we can write:

$$y_i(t) = \begin{cases} w_s(t) + \kappa\left[(1-p)\lambda_0 n_{B1}(\omega,t)^{-a} - AD(t)\right] & \text{if } \omega \in A_1 \\ w_s(t) + \kappa\left[\lambda_0 n_{B0}(\omega,t)^{-a} - AD(t)\right] & \text{if } \omega \in A_0 \end{cases} \tag{14}$$

where $AD(t)$ is the aggregate expected number of discoveries per-basic research labour, to be computed later from basic research equilibrium allocations. Notice that we are assuming that the researcher's time is fully absorbed by the sector ω he/she chooses. This indivisibility is just to facilitate the reader, but it is not needed at all: in fact, the indifference condition to be derived soon guarantees any allocation, hence restoring full consistency with the representative agent parable.

Scheme (14) can also be re-interpreted in terms of non-economic rewards: according to this interpretation, κ measures the pecuniary equivalent of an additional unit of "status", which is granted by the researcher's community in recognition of his/her awareness of social needs when undertaking basic research[14]; moreover, detection probability p measures how closely the community can monitor the individual researcher, thereby being affects by the prevailing level of social capital in the economy. According to the recent interesting empir-

[13] We could cite plenty of press articles and books making arguments in this direction.

[14] In a similar way, among the motivations of Open Source programmers is "ego gratification from peer recognition" (Lerner and Tirole, 2005, p. 103). We all know the useful effects for application of such a social norm, favored by a kind of electronic social capital. According to the same authors, "As in open source, the direct financial returns from writing academic articles are typically nonexistent, but career concerns and the desire for peer recognition provide powerful inducements", (Lerner and Tirole, 2005, p. 116-117). See Maurer and Scotchmer (2006) for an excellent interdisciplinary survey of the literature about this complex phenomenon.

ical analysis of Akcomak and Weel (2009), probability p should have a positive effect on the long-run equilibrium innovation rate in the economy.

4 Equilibrium

Since "half-ideas", lacking direct industrial applicability, are not patentable, no private research firm will be looking for them. Let $\bar{L}_G$ denote the total mass of researchers employed in the public laboratories; hence it must be: $\int_{[0,1]} n_B(\omega,t)d\omega = \bar{L}_G$. Research tools discovered by public laboratories will be available to everyone, which implies that private R&D firms will flood into the A_1 sectors, racing to patent the new final product.

We will study symmetric equilibria, in which $n_A(\omega,t) \equiv n_A(t)$, and

$$n_B(\omega,t) = \begin{cases} n_{B0}(t) & \text{if } \omega \in A_0 \\ n_{B1}(t) & \text{if } \omega \in A_1 \end{cases}$$

In equilibrium, the basic researchers will allocate themselves over the set of industries, that is:

$$\bar{L}_G = n_{B0}(t)m(A_0) + n_{B1}(t)m(A_1). \tag{15}$$

In light of the definitions so far, dropping time indexes, we can express the skilled labor market equilibrium as:

$$L = \bar{L}_G + m(A_1)n_A. \tag{L}$$

Eq. (L) states that, at each date, the aggregate supply of skilled labor, L, finds employment in the public R&D laboratories, $\bar{L}_G$, and in the R&D firms of the A_1 sectors, n_A. Therefore the mass of skilled labour employment per A_1 industry is:

$$n_A = \frac{L - \bar{L}_G}{1 - m(A_0)}. \tag{16}$$

The dynamics of the industries is now described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\, \lambda_1 n_A^{1-a} - m(A_0)\lambda_0 n_{B0}^{1-a}.$$

In light of eq. (16), it can be written as:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\, \lambda_1 \left(\frac{L - \bar{L}_G}{1 - m(A_0)}\right)^{1-a} - m(A_0)\lambda_0 n_{B0}^{1-a}. \tag{17}$$

In equilibrium, the researcher will be indifferent as to where to target his research, which implies, by eq. (14) and symmetry (and dropping time indexes), that: $(1-p)n_{B1}^{-a} = n_{B0}^{-a}$. Therefore, $\frac{n_{B1}}{n_{B0}} = (1-p)^{\frac{1}{a}}$. Using eq. (15), we obtain:

$$n_{B0} = \frac{\bar{L}_G}{(1-p)^{\frac{1}{a}}\left[1-m(A_0)\right]+m(A_0)} \tag{18}$$

and

$$n_{B1} = \frac{\bar{L}_G(1-p)^{\frac{1}{a}}}{(1-p)^{\frac{1}{a}}\left[1-m(A_0)\right]+m(A_0)}$$

These in turn imply that the recorded (and approved) number of discoveries expected per unit of public research labour - and hence the correct value of AD - is

$$\begin{aligned} AD &= \frac{n_{B0}^{1-a}\lambda_0 m(A_0)+(1-p)n_{B1}^{1-a}\lambda_0\left[1-m(A_0)\right]}{\bar{L}_G} = \\ &= \lambda_0\left(\frac{(1-p)^{\frac{1}{a}}\left[1-m(A_0)\right]+m(A_0)}{\bar{L}_G}\right)^a. \end{aligned}$$

Obviously, only part of this flow of basic research results turn out to be useful to the industries. This flow of useful "half ideas" is given by:

$$\lambda_0 n_{B0}^{1-a} m(A_0) = \lambda_0\left(\frac{\bar{L}_G}{(1-p)^{\frac{1}{a}}\left[\frac{1}{m(A_0)}-1\right]+1}\right)^{1-a} m(A_0)^a. \tag{19}$$

Ceteris paribus, an increase in the public sector accuracy in prizing useful inventions - represented by our parameter p - generates an increase in the number of basic research results per unit time. Notice that, in our incentive scheme, it is not the absolute amount of the prize κ that matters, but only the accuracy in the screening process. Moreover, given the "rat race" aspect of our reward[15], no payment is required from the government on average. In fact, AD is equal to the expected number of discoveries per unit time, which is the same for each basic researcher regardless of his/her product line choice.

Eq. (19) gives the flow out of the A_0 sector, which, in a steady state, coincides with the flow out of the A_1 sector, i.e. with the economy-wide innovation rate. That innovation rate is maximal and equal to $\lambda_0\bar{L}_G^{1-a}$ when $p=1$. This emphasizes the importance of public institutions' being careful in prizing only the potentially useful basic research results, that is in successfully discouraging the neglect of social needs by the basic researchers.

Plugging eq. (18) into (17) gives:

$$\frac{dm(A_0)}{dt} = (1-m(A_0))^a\lambda_1\left(L-\bar{L}_G\right)^{1-a} - m(A_0)^a\lambda_0\left(\frac{\bar{L}_G}{(1-p)^{\frac{1}{a}}\left[1-m(A_0)\right]+m(A_0)}\right)^{1-a}. \tag{20}$$

[15] Cozzi (2004) showed the potentially important growth and fiscal policy effects of status seeking motivations, in a model of physical and human capital accumulation.

This is a first order differential equation in $m(A_0)$, which is globally stable. In fact, the right hand side is continuous and strictly decreasing in $m(A_0)$; moreover it is positive for $m(A_0) = 0$, and it is negative for $m(A_0) = 1$, as immediately checked. Therefore $m(A_0)$ always tends to $m(A_0) = \tilde{m}_0 \in]0,1[$.

In a steady state, eq. (20) implies:

$$(1-\tilde{m}_0)^a \lambda_1 \left(L - \bar{L}_G\right)^{1-a} = \tilde{m}_0^a \lambda_0 \left(\frac{\bar{L}_G}{(1-p)^{\frac{1}{a}} (1-\tilde{m}_0) + \tilde{m}_0} \right)^{1-a}. \tag{21}$$

From the implicit function theorem, we obtain $\frac{d\tilde{m}_0}{dp} < 0$. Therefore

$$\frac{d}{dp}\left[(1-\tilde{m}_0)^a \lambda_1 \left(L - \bar{L}_G\right)^{1-a}\right] > 0.$$

Since $(1-\tilde{m}_0)^a \lambda_1 \left(L - \bar{L}_G\right)^{1-a}$ is indeed the steady state innovation rate in the economy, the following proposition holds:

Proposition 1 *The higher the government accuracy in prizing basic research, p, the higher the steady state equilibrium innovation rate of the economy. This effect is increasing in L and decreasing in $\bar{L}_G$. The amount of the prize, κ, plays no role as long as it is positive.*

As previously mentioned, we can reinterpret prize κ as the marginal social status conferred to the basic researchers who invent more useful research tools, as compared to those who just think of shortcuts at enriching their CVs. Consistently, we can re-interpret detection probability p as the consequence of higher levels of social capital, which guarantees more accuracy in the status awarded to the most socially aware basic researchers. Hence we can state:

Proposition 2 *The higher social capital the stronger the effect of status-seeking altruism on the equilibrium innovation rate.*

This is in line with Akcomak and Weel's (2009) empirical finding of a positive effect of social capital, measured in by the level of trust, on innovation and growth in 102 European regions.

Unlike Cozzi and Galli (2008), here we do not need to solve for the rest of the variables (values of patents and firms, skill premium, etc.), but the readers could easily do it by themselves along the lines of that paper. The reason why the derivation of the steady-state equilibrium innovation rate is much simpler here is that the skilled labour is assumed employed only in the R&D sectors. Cozzi and Galli (2008), instead, assumed that skilled labour was used both in R&D and in manufacturing, which complicated the model a lot, but of course allowed for the skill premium to play an important allocative role: such greater realism justified the real world calibrations, which would be hardly credible in the current model. However, the advantage of our simpler formulation is to deliver rigorous analytical results in a transparent way.

5 Final Remarks

This paper has incorporated monetary and non-monetary incentives to public basic research, within a general equilibrium R&D-driven growth model in which the innovation process is decomposed into two successive innovative stages. We have shown that public research institutions' targetness as well as social awareness supported by social capital may matter for innovation and growth.

The extension of multisector Schumpeterian models to a relatively realistic dimension - multi-stage R&D - allows us to depict a stylized economy similar to the current European system of innovation, and to set a potentially useful framework for an assessment of potential US-oriented policy shift towards the extension of patentability to research tools and basic scientific ideas. These normative innovations have been modifying the US industrial and academic lives in the last two decades. In a useful assessment of the publicly run basic research, we emphasize the crucial role of the public researcher's social awareness of the potential utility of their intellectual discoveries. If they try to target their research efforts where society really need, they will positively affect long run per-capita growth.

The recent decades have witnessed a significant increase in the number of patents issued every year by the U.S. Patent and Trademark Office (PTO): in 1980 the PTO issued approximately 66,000 patents; in 2000 such number had grown to 175,000[16]. Many scholars addressed as a reason for the increase in the overall patenting activity in U.S. the changing legal environment that opened the way to the so called "pro-patent era", de facto strengthening the rights of the patent holders (see Gallini, 2002; Cozzi and Galli, 2008). Other authors (for example, Kortum and Lerner, 1998) commented that this increase may have somehow reflected an increased innovation activity spurred by changes in the management of research. Our model, by highlighting a possible channel, suggests that, in the US after 1980, institutional and cultural changes have connected basic and applied research more than before, i.e. the academic and the industrial worlds looked at each other more friendly. This in turn encouraged more public researchers to exit the ivory tower, with the economy benefiting from this shift.

Economic history from the end of the feudal era to nowadays showed us how law and society are always mutually linked in a dialectic way, such that the one is able to determine the other's morphology and together flow into the cultural change. We could think about the Bayh-Dole act[17] and the series of patent system reforms incurred in the U.S. at the beginning of the Eighties as endogenous or culturally determined; consistently with the assertion of David Mowery : "*Bayh-Dole is an effect of growth in US university patenting during*

[16] US Patent Statistics from the United States Patent and Trademark Office, available at http://uspto.gov/web/offices/ac/ido/oeip/taf/apat.pdf.

[17] In the U.S. the passage of the Bayh-Dole Act in 1980 simplified the patenting of government-supported research outputs, which are often upstream to the development of innovative marketable products.

the 70s, as well as one of the several causes of increased academic patenting during the 80s".

Whenever direction the causality goes, what is certain is that during the thirty years following the passage of the Bayh-Dole Act US universities experienced a serious attempt to re-optimize, or to better balance the objective of developing new revenue sources while simultaneously maintaining the norms related to the conduct of academic research[18].

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