Incentive structure in basic research and economic growth

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1 Introduction

Study of the causes of economic growth since the industrial revolution has highlighted the importance of technological development in long-run economic dynamics. This interpretation of long-period growth has come to the fore in the applied literature, and recently also in the theoretical literature which reprises Schumpeter's theories of the first half of the 1900s. On closer inspection, however, this interpretation is incomplete because it fails to consider the origin of technological advancement, namely the progress of science. Historians and scholars of science, in fact, stress the concomitance between the appearance of important scientific discoveries and the transition from a period of slow productivity growth to that of exponential expansion which led up to the contemporary age.

The alliance between basic research, technology and growth has been particularly close and fruitful since the nineteenth century. Rosenberg and Birdzell (1986; 1990) argue that economic miracle of the Western world can be explained by the marked increase in science's ability to investigate the secrets of nature since the end of the 1800s. This greater efficiency of basic research was initially due to important changes in its organization and closer interaction with the rest of society and with the economy. The creation of institutions to host and remunerate scientists was accompanied by the increasing specialization of research work into departments and the emergence of norms within the scientific community which regulated its activity.

The period saw the founding of prestigious journals which collected and disseminated the results of scientific inquiry. The peer reviewing of articles allowed the objective assessment of the products of research and enabled scientists to receive recognition from their community in terms of prestige.The spread of experimental research work in equipped laboratories favoured closer interaction between scientific research and technological research which generated radical innovations and strong growth of productivity.

In this chapter we put forward an analytical approach to economic growth which tries to capture the essential features of the interaction between the work of the scientific community and long-period economic activity.

The traditional theory of growth, which originated with Solow (1956), considers the academic world to be exogenous with respect to the economy. As in the case of other public goods, the production of knowledge is the task of the state. Advances of basic research and those of applied research constitute Solow's 'residual' - the unexplained part of the growth of per capita output. Exceptions in this theoretical tradition are the works of Karl Shell (1969, 1970), in which the production of knowledge is endogenous. In this model, the state collects resources from the activities of private agents in order to finance basic research, which is the public input to the private sector. The economic problem analysed by Shell is essentially that of the dynamic allocation of resources between the production of goods and the production of knowledge. Still largely unexplored in the economics literature is the scientific research sector in relation to its forms of organization and the incentives - economic and otherwise - which motivate those who work in it.

With the advent of 'endogenous growth theory' - the new scientific paradigm for the analysis of growth - innovation has become a central topic of inquiry. The works of Romer (1990), Aghion and Howitt (1992), and Grossman and Helpman (1991) have generated a rich Schumpeterian strand in growth theory which draws heavily on the microeconomic literature on industrial innovation in which innovative firms get a patent that prevents others from profiting from new knowledge. These models, too, relegate the production of new opportunities for technological progress to a residual domain exogenous to the economy. The case of growth models with general purpose technology is emblematic of the limitations of this approach. GPTs, in fact, are radical changes in technologies which improve production possibilities in a wide range of sectors. These changes should certainly be associated with scientific advances which alter the constraints to which technologies are subject, but there is no trace of this phenomenon in these models.

The influence of scientific advances on technological innovation, and on the productivity of economic systems, has been the subject of applied inquiry for a number of years. The studies by Mansfield (1991, 1995) are based on surveys of firms' opinions on the importance of scientific advances for innovation in products and processes. The first study was based on a sample of 76 of the largest USA firms and found that in the period 1975-1985 around 11% of new products and 9%

of new processes could not have been developed without the results of academic research conducted in the previous fifteen years.

An equally direct approach has been used by Adams (1990), who estimates the contribution of scientific knowledge to productivity growth in 18 manufacturing sectors. The main feature of this study is its meticulous construction of an indicator of the stock of scientific knowledge obtained by considering both the number of publications in scientific fields closest to the sector's technology since the 1930s, and the scientific personnel employed in the sector.

Another strand of studies consider the spatial effects of research spillover on the innovative activities of firms. Among the most important of these studies is Jaffe (1989), which considers data on corporate patents in each state of the USA. The estimation of a model of simultaneous equations shows that there are important spillover values for academic research, especially in the cases of pharmaceuticals and chemicals industries.

In spite of scant growth theory dealing with basic research, economists (Arrow, 1962; Nelson 1959) have long concerned themselves with the world of scientific research. Indeed, the studies of the past two decades have given rise to what has been termed the 'economics of science' (see Stephan, 1996). This comprises the numerous empirical works that have investigated the connections between scientific production and technological innovation, as well as those which study the labour market of scientists. Recently, a number of theoretical analyses have shown the substantial differences between the activities of basic research and those of technological innovation. Dasgupta and David (1987; 1994) have constructed a theoretical framework - still highly general and open - with the components essential for the analytical representation of the production of basic knowledge.

In this framework, the state organizes the scientific sector because the output from scientific research is considered to be a public good because of its non-rival nature and because of the full disclosure rule adopted by researchers when they obtain new results. The 'quest for priority' as the essential motivation of researchers is a decisive aspect of the theory imported from the sociology of science (Merton, 1957). Researchers compete against each other for rewards, which take the form - in the case of success - of important publications and the consequent advantages in terms of income, prestige and reputation. Hence, unlike the objective of those who work in applied and technological research, that of scientists is to achieve the widest possible circulation of their findings, rather than secrecy.

In these winner-take-all contests there is great uncertainty over the outcome, and the problem of incentives is particularly acute because of the difficulty of monitoring effort. Actually, academic researchers also earn a certain wage that provides incentives for effort in research that otherwise could be too low as a consequence of uncertainty. Teaching also provides a source of income alternative to research. The literature on academic research agrees that the incentives system prevalent in the sector efficiently motivates workers, so that problems of shirking are rare.

The organization of work in academic research is strongly characterized by different forms of cooperation and knowledge-sharing, albeit in the presence of strictly personal goals and fierce competition. In fact, there are several informal sources of externalities in basic research. Scientists share and confront their ideas while talking with other scientists, or in seminars. This is one reason for the assignment of prestige to academic departments. Furthermore, peer evaluation and reciprocal recognition of the value of discoveries are forms of externalities which closely influence the productivity of individual researchers.

The model analysed in this paper represents the working of an economy which consists of agents who may choose to work either in the goods production sector or in scientific research. These two economic activities are organized according to different objectives and rules. Research is financed by the state out of taxes, and its output is a public good that benefits all firms and improves their productivity. Researchers are engaged in competitions with other researchers for a new discovery. The probability of a new finding by a researcher is a function of his/her effort, and his/her interactions with other researchers. Our model has a strong focus on scientists incentives. In fact we assume three forms of reward. In each race in basic research the state rewards with a prize only the winner, and this monetary prize lasts until the arrival of a new discovery. Every scientist also receives a fixed salary that does not depend on effort and success in research. The third type of reward is nonmonetary as it concerns prestige and social status, a relevant determinant of effort in basic research. We propose such an incentive scheme in order to account for the main features of scientist work. In fact, even though the quest for priority makes effort very high, it must be considered that scientists have a guaranteed salary that may reduce the negative effects on incentives of such winner-take-all contests. Furthermore, scientists who win a race cannot "rest on their laurels" because science goes on and new findings may make obsolete the previous.

This model produces some interesting results concerning the effects of the organization of science sector on economic growth. Among the main results of the analysis of the model are the possible existence of multiple steady state equilibria that can usefully characterize advanced countries and undeveloped countries. Non-monetary incentives to work in basic research, as social prestige and conformity, may induce high effort and foster economic growth, even if their effects are not straight. Public policices aimed at enlarging the science sector should balance the positive effects of higher prizes and salaries to scientists with the negative effects on the private sector.

The paper is organized as follows. The second section surveys the theoretical literature on the relationship between science and economic growth. The third section sets out the basic theoretical model. The fourth section analyses the model's equilibrium solution.

2 The economics of science

Arrow's 1962 essay laid the basis for the economic analysis of the production of and the demand for knowledge; analysis that was subsequently developed with reference to technological innovation. In the very general terms of Arrow's analysis, the various forms that knowledge can assume are likened to information. According to Arrow, on the supply side, once knowledge has been produced it can be transmitted at a cost considerably lower than that necessary for its production. On the demand side, information has the characteristic of non-rivalry in its consumption, because its use by one individual does not reduce the quantity available for consumption by another individual. These two features of knowledge make it similar to a public good - all the more so the greater the degree of excludability in consumption, which cannot be perfect.

Arrow's article prompted Dasgupta and David (1987) to investigate the fundamental differences between the production of knowledge in the institutions of science and technology. This important essay laid the basis for the modern economic theory of science. The main differences between the worlds of science and technological innovation reside in their organization and the goals pursued. The fundamental difference between science and technology concerns the dissemination of results, which is immediate and complete in scientific research as academic researchers seek to publish their discoveries as soon as possible and obtain, through peer evaluation, recognition by the scientific community of the validity of their results.This is contrary to what happens in technological research where new knowledge is kept secret..

The scientific community on the one hand enjoys the advantage of complete information; on the other, it is concerned to ensure the researcher's property right on the item of new knowledge that s/he has produced. Because full disclosure is the optimal solution from the point of view of society's well-being, this social norm adopted in the scientific community serves that purpose. Obviously, full disclosure conflicts strongly with the secrecy necessary to be able to profit from technological innovation. Firms, in fact, obtain a return on investments in R&D in relation to the degree of market power that a patent or the restricted circulation of an innovation may generate for them. Radically different from this objective is the 'quest for priority' in attribution of the paternity of a discovery that motivates academic researchers. The latter immediately submit the results of their work for publication which will certify their priority in the discovery. From this derives recognition in monetary terms (career advancement, awards, etc.) and in terms of reputation and prestige in the scientific community.

The incentives system that operates in research is characterized by great uncertainty and by the principal's difficulty of monitoring effort. The evolution of state-organized academic research seems to have struck a balance between the private motivations of researchers and the needs of society. Individual scientists take part in contests in which those who obtain an innovative result first receive recognition from the scientific community and the advantages that ensure therefrom.

Because the work of those who do not win is valueless, the contest belongs to the category of tournaments in which the winner takes all (Dasgupta, 1989; Lazear, 1997). Comparison with reality shows that this system efficiently incentivizes academic researchers, in that they are generally highly motivated and committed to their research. In effect, this result also derives from the assurance of an income, often from teaching duties, which mitigates the effects of the risk in research.

The rules of the academic world favour the spread of forms of collaboration and information-sharing which have important externalities. Work in academic departments is characterized by forms of knowledge sharing and ideas' discussion as seminars and mimeo circulation and also by several informal ways of externalities in everyday life interactions. The transmission of tacit knowledge takes place in academic departments whose composition is an important factor in the work of individual researchers. This relationship may also hold among researchers belonging to different institutions but who work in the same field and interact with each other to form 'invisible colleges' (David, 1998). Furthermore, scientific work is often carried out by teams of researchers, in that the advantages deriving from obtaining priority are generally indivisible, while the pooling of kindred and specialized skills considerably increases the chances of success (Stephan and Levin, 1992). Data on publications show that collaborations have increased over time.

Externalities in knowledge production have been analyzed by Carraro, Pomè and Siniscalco (2001) in a model that concerns a race between academic researchers and researchers in private firms to a specific discovery with possible commercial use. This paper shows under what conditions the coexistence of Science and Technology institutions can be welfare maximizing.

The topic of incentives for academic researchers also relates to the aggregate size of the scientific research sector compared with that of technological research and the economy in general. From a long-period perspective, scientific knowledge is a crucial input to technological innovation. Consequently, in the long period, it is necessary for a balance to be struck between the incentives for scientific research work and the economic advantages in technological research increased by innovations.

3 The Economy

A class of growth models that can be used to represent the salient features of the science sector described in the previous sections comprises so-called neo-Schumpeterian models. Here we follow the framework of Aghion-Howitt (1992) in which there is no capital accumulation.

In our economy there is a continuum of individuals, of measure 1, who can find employment in one of two different sectors: one is a competitive consumption good sector, the other is the basic research sector which produces the body of knowledge used in the production process of the final good. Manufacturing firms are owned by all agents in the economy, and labour and capital markets are perfecly competitive. The state owns and organizes the science sector.

Each individual has an infinite life-span and is characterised by one (identical for all agents) intertemporal utility function of consumption and effort required by the job performed. The intertemporal preference rate, $r > 0$, is constant and in equilibrium coincides with the rate of interest at which firms collect savings. Time is indexed by t, while the state of knowledge is indexed by k.

The consumption good, which acts as numeraire, is produced using the following technology:

$$Y_{k_t} = R_k l_{k_t}^{\alpha} \tag{1}$$

with $0 < \alpha < 1$, where l_{k_t} denotes the number of specialised workers used at time t and R_k is a technological parameter which measures the productivity of the basic knowledge freely disposable in the technological era k.

In this economy, innnovation consists in the birth of a new body of knowledge, $k + 1$, produced in the science sector, able to increase the productivity of final good workers by a constant parameter $\gamma > 1$. That is to say, as common in Shumpeterian growth models, we assume that:

$$R_k = \gamma^k \tag{2}$$

Consequently k denotes the type of basic knowledge and the technological era that comes to an end with a scientific discovery and the introduction in manufacturing of an innovation. Because the parameters that define the economy, and therefore the choices made by the agents, remain constant during each technological era, henceforth we can simplify the notation by omitting the time index t when it is not indispensable.

3.1 Science sector

Science sector in this economy produces the new basic knowledge which is a public good freely disposible for the production of the final good. As is well known, public good production usually involves strong problems with workers' incentives and effort. In our model, this issue is crucial since new knowledge production - hence economic growth - depends on effort of scientists. Actually, as Robert Merton (1957) pointed out, the science sector has developed a reward system particularly complex and efficient based on both a recognition mechanism and a monetary reward which provide strong incentives to the production and dissemination of knowledge by enhancing in the same time the productivity of the best and most original scientists. Moreover, monetary reward and social reward interact in an important way through the norms which regulate the working of the academia.

The main characteristic of the academia is the high value attached to the priority of discovery. As a consequence of the norm of "priority" in scientific discoveries researchers compete in contests to be the first who introduces an innovation, and be rewarded by the scientific community

In this "winner take all" contest, the prize has a multidimensional nature, given that it consists in a monetary reward and in a high esteem or peer-recognition which usually takes the form of honorific awards, memberships in honorific societies or in prestigious departments. The monetary reward is funded by the State, while the esteem derives from peer recognition in the form of citations of their work, invitation to speak at important gatherings and awards. Scientists are not interested in recognition received from external agents, rather what they want is recognition from their peers[1].

Formally, in each instant t, the benefits deriving from being an innovator, $v_{k+1,t}$, are:

$$v_{k+1,t} = m_{k+1,t} + P_{k+1,t} \tag{3}$$

[1] David Raup (1986) coined the phrase "saganization" to describe the loss of professional reputation that a scientists suffers after receiving continued mass media attention.

where m_{k+1} is the monetary reward while $P_{k+1}$is the social reward, both gained when innovation occurs and therefore gained in the technological era that follows that when the research activity is carried out. Moreover, since there can be only one winner a time, both types of prize will last untill a new innovation and a new tchnological era arrives.

The social prestige deriving from innovation is given by the following function:

$$P_{k+1} = \varphi(n_{k+1}) P_0 R_{k+1} \tag{4}$$

where P_0 is a parameter and $\varphi(n_{k+1})$ represents the recognition function, which increases as the size of the research sector rises, even if at a decreasing rate. More particularly we have that:

$$\varphi(n_{k+1}) = n_{k+1}^{\beta}$$

with $0 < \beta < 1$.

In other words, we assume that social prestige is positively related to the value of innovation introduced and, since it depends on the peers recognition, prestige increases if the latter increases.

In this model innovation is uncertain and, following the literature on patent races, we assume that the probability that a single researcher obtains an innovation depends on the effort that he devotes to the research actitivity, and follows a poisson stocastic process with a parameter given by:

$$\theta(x_k) = \theta x_{k_t} + \theta h \overline{x}_{k_t} \tag{5}$$

where x_k is the effort employed by the scientist in the research activity, $\overline{x}_k$ is the average effort of the research sector, and $\theta > 0$ and $h > 0$ are two parameters. Equation indicates that the poisson parameter, which gives the probability that a single researcher innovates, depends positively upon the effort of scientist and upon the average effort of the whole research sector. While, as concerns the probability that an innovation occurs in the economy, we have : $\theta n_k(x_k + h\overline{x}_k)$.

The hypothesis of externality effects on "productivity" of a single researcher captures the role of colleagues, which is of a paramount importance in doing science.

Good science is done in communities of scientists and often in teams. Cooperation in science extends far beyond team players, regardless of wheather they are team members, scientists talk with other scientists, share ideas, discuss one another work. This occur in informal way and in formal presentations of seminars and papers. The interchanges that result from such discussions can make spectacular differences in science. The importance of colleagues goes beyond the boundary of the particular institution with which the scientist is affiliated, since the productive scientist is also likely to belong to an "invisible college" (David, 1998), a group of scientists who share common interests, and meet formally and informally to exchange ideas. These "invisible colleges" play a significant role in science by furthering knowledge and establishing research agenda.

The importance of the group externalitites is enhanced also by the rules which govern the academia, in fact the rule of priority induces to exchange ideas in order to obtain as early as possible the recognition of others, in other words, it works the rule of "full disclosure" (Dasgupta and David, 1994) that increases the interconnections among researchers and the externalities effects.

To capture such important aspects we have assumed that the productivity of a single researcher depends not only upon his own effort but also upon the effort put in the research activity by his colleagues, rapresented by the average effort of the scientists group. We use the average effort since it better represents the intellectual and psychological resources of others to which scientist may have access, which are relevant not only for their quantity but rather for their quality.

Given the above hypothesis the total expected benefits deriving from being an innovator are:

$$V_{k+1} = \theta(x_k + h\overline{x}_k) \int_{t_0}^{\infty} e^{-[r+\theta n_{k+1}(x_{k+1}+h\overline{x}_{k+1})](t-t_0)} v_{k+1} dt \qquad (6)$$

Substituting in this expression in equations (3) and (4) and solving the integral we have:

$$V_{k+1} = \frac{\theta(x_k + h\overline{x}_k)m_{k+1}}{r + \theta n_{k+1}(x_{k+1} + h\overline{x}_{k+1})} + \frac{\theta(x_k + h\overline{x}_k)P_{k+1}}{r + \theta n_{k+1}(x_{k+1} + h\overline{x}_{k+1})} \tag{7}$$

The rule of priority assures that the prize is obtained only by the innovator, but this implies that the losers of a scientific race receive absolutely nothing. This is a problem because in this case the rule of priority places all the risk of innovation activity on the shoulders of scientists and this cannot be efficient. To overcome this problem usually the scientists' payment schedule consists not only of the prize for being the winner of scientific competition, but also of a flat salary which is received just for entering science. Often this salary is connected with some other activity not directly linked to research (for example teaching).

In order to capture this important characteristic of scientists' incentive scheme, we assume that the researcher receives a fixed salary F_k, funded by the state, obtained only for entering the science sector, which lasts untill the individual is in the science sector.

Scientists to obtain scientific output use essentially cognitive resources and effort, in particular the latter is very important since it is strongly related with the motivation, the dedication to do science and therefore with the cognitive resources. Mary Frank Fox (1983), a sociologist of science, notes that certain investigations have shown that "productive scientists, and eminent scientists especially, are a strongly motivated group of researchers" and have the "stamina" or the capacity to work hard. Empirical data on scientists do suggest that high performers are absorbed, involved and strongly identified with their work. This implies that psychological variables and motivation to do science may interact with the capacity to bear high level of effort by reducing the disutility deriving from it. In other words motivation to do science makes less costly to work hard.

Motivation to do science is also related to the social recognition and to the comparison with own colleagues. Scientists who stay in highly motivated environment, where there is an high identification with the science and an "ethics" of work, attach an high social esteem to collegues who bestows an high level of effort in their activity.

In order to consider this dimension of the reward from doing science, that linkes social interactions and the degree of application of human resources, we assume that the cost of effort, expressed in terms of utility, is reduced by reputational effects, which rises the motivation to do science. More particularly, we have assumed that social esteem of a researcher is higher, harder he works with respect to his colleagues. Formally the cost of effort ($c(x, \overline{x})$) is:

$$c(x_k, \overline{x}_k) = R_k \left[dx_k - s(x_k - \overline{x}_k)\right]^{1+\sigma} \tag{8}$$

with $\sigma > 0$.

Moreover we assume that $(d - s) > 0$. This assumption assures that social esteem is not so high to make convex the utility function (i.e. to make $c(x_k, \overline{x}_k) < 0$).

Given the above hypothesis the total expected benefits deriving from partecipate in the research sector is given by the following:

$$U_{R,k} = \int_{t_0}^{\infty} e^{-[r+\theta n_k(x_k+h\overline{x}_k)](t-t_0)} \left[V_{k+1} + F_k - R_k \left[dx_k - s(x_k - \overline{x}_k)\right]^{1+\sigma}\right] dt \quad (9)$$

3.2 The consumption good sector

In the consumption good sector each worker can supply inelastically one unit of labour factor, and there is no disutility connected with work. Given these assumptions, the expected utility obtainable by workers in this sector is:

$$U_{y,k} = \int_{t_0}^{\infty} e^{-[r+\theta n_k(x_k+h\overline{x}_k)](t-t_0)} w_k = \frac{w_k}{r + n_k(\theta x_k + \theta h\overline{x}_k)} \quad (10)$$

where w_k is the wage obtainable in that sector.

Consumption sector receives technology from the research sector at no cost, but it pays taxes that the state uses to fund the research sector. Considering the production function (1) and bearing in mind that this sector operates in perfect competition, profits net of taxes are defined as follows: $\pi = (1-\tau)Y_k - w_k l_k$, where τ denotes the tax rate. Maximization of this function yields the wages in the consumption good sector, as given by:

$$w_k = (1-\tau)\alpha R_k l_k^{\alpha-1}. \tag{11}$$

3.3 The public sector

The state levies taxes, τY_k, on the consumption good sector in order to finance production of knowledge by the research sector. The financing consists in an amount of monetary income which is distributed only to those who win the scientific discovery contest. We have repeatedly emphasised, in fact, that the income of researchers working in the public sector consists of a share connected with innovative activity - i.e. a reward paid only if innovation is produced - and a share which is instead independent of production of innovation, and which shelters researchers against the risk of not producing any innovation.

Given these hypotheses, we have:

$$m_k = \tau_1 Y_k \tag{12}$$

$$f_k n_k = \tau_2 Y_k \tag{13}$$

where $\tau = \tau_1 + \tau_2$, and τ_1, τ_2 represent the shares of private income that go to finance the prize of scientific races and to the fixed salary of researchers. Hence, the state's budget constraint can be represented as follows:

$$m_k + f_k n_k = \tau Y_k \tag{14}$$

4 Equilibrium

Equilibrium in this economy is defined by both the optimal level of effort that each scientist puts in the research acitvity and in the optimal number of scientists that are allocated to the science sector.

The optimal level of effort undertaken by scientists, x_k, maximizes the present net value of the total expected benefits deriving from doing research. We assume that a scientist does not have a strategic behaviour so that she does not consider the effect of her effort on the arrival rate of discoveries in the economy. In this case, the maximization of the total benefits gives rise to the following first order equilibrium condition:

$$\frac{\theta(m_{k+1} + P_{k+1})}{r + n_{k+1}\theta(x_{k+1} + h\overline{x}_{k+1})} - (d - s)(1 + \sigma)R_k \left[dx_{k_t} - s(x_k - \overline{x}_k)\right]^{\sigma} = 0. \tag{15}$$

According to equation (15), each researcher chooses the optimal amount of effort by equating the expected discounted marginal benefit of one more unit of effort to the marginal disutility that derives from effort, in which the negative effect of higher effort is weakened by stronger status in the scientific community.

The optimal choice of effort depends on n_{k+1}, the dimension of science sector. Since individuals can choose, without sustaining costs, to participate in the labour market either as workers in the consumption sector or as researchers in the science sector, in equilibrium the maximum utility yielded by the two types of activity should be the same. By equations (9) and (10) we have the following equilibrium condition for the labour market:

$$V_{k+1} + F_k - R_k \left[dx_{k_t} - s(x_k - \overline{x}_k) \right]^{1+\sigma} = w_k \tag{16}$$

Given that individuals are homogeneous, equilibrium will be simmetric, which implies that $x_k = \overline{x}_k$. Finally, in equilibrium all individuals find employment, then we have: $n_k + l_k = 1$.

The analysis of dynamic equilibrium derives from the last three equilibrium conditions. Firstly, from equilibrium conditions eq. (15) and eq. (16) we are able to write x_k as a function of n_k:

$$x(n_k) = \left\{ \frac{(1-n_k)^{\alpha-1}\left[\alpha(1-\tau_1) - \tau_2\left(\frac{1}{n_k} - 1 + \alpha\right)\right]}{(1+\sigma)(d-s)(1+h) - d} \right\}^{\frac{1}{1+\sigma}} \tag{17}$$

By the above expression, we can note that $x(n_k)$ is increasing and, in order to have a positive value of effort, the dimension of science sector must be greater than a threshold: $n_k > \frac{\tau_2}{\alpha(1-\tau_1)+(1-\alpha)\tau_2} \equiv \underline{n}$. More, the optimal choice of effort goes to infinity as $n \rightarrow 1$.

From the above condition we can see that the component of total reward not linked to the innovation- i.e. the flat salary- may have a perverse effect on the level of effort. Hovewer this perverse effect can be compensated by a high reputational reward deriving from being a strongly motivated scientist.

Another result that emerges is the positive relation between the optimal level of effort and n_k. This relation can be explained by the fact that as the size of science sector increases, wage in the consumption sector, which is the alternative sector, also rises, while the fixed salary is reduced, by reducing at the same time the perverse effect of this latter on the scientists'effort.

Simple exercises of comparative statics on equation (17) allow us to analyse the effects that some relevant parameters have on the optimal level of effort directly, i.e. without the consideration of indirect effects which work through variations in the size of science sector. The results are summarized by the following:

Proposition 1 *Given employment in science sector n_k, the equilibrium level of* *effort of researchers* x_k*:*

- *increases as status effects - s - become stronger;*
- *decreases when externalities - h - and the share of resources invested by the state in the research activity -* τ_1, τ_2 *- are higher. The negative effect of* τ_2*, the fixed salary component of scientists income, is stronger than the effects of* τ_1*.*

Proof. It follows trivially from simple partial derivatives with respect to τ_1, τ_2, h,and s,by considering n_k constant. ■

As expected, the status variable has a positive direct effect on the level of effort, while concerning the direct effects of externalities and of the state resources, the results of Proposition 1 seem to be counterintuitive. However they can be explained by considering that externalities reduce the period during which a successful scientists can enjoy her prize. As far as the effect of public funds to research is concerned, we have to consider that the wage received in the alternative sector will be reduced by an increase in τ_1 and τ_2 and, given the labour market equilibrium condition, this reduces also the reward to all the specialized workers. It can be noted that parameters concerning prestige do not affect effort, but later it will be clear that they affect employment in science n.

However, these are only partial effects that do not take into account the indirect effects which work through the induced variations of the optimal number of individuals that in the technological era k are employed in the science sector.

To find these latter we substitute equation (17) in equation (16) obtaining the following difference equation in the variable n_k:

$$\Psi(n_{k+1}) = \Theta(n_k) \tag{18}$$

where

$$\Psi(n_{k+1}) \equiv \frac{\theta\gamma\left[\tau_1(1-n_{k+1})^{\alpha} + P_0 n_{k+1}^{\beta}\right]}{r + \theta(1+h)n_{k+1}\left\{\frac{(1-n_{k+1})^{\alpha-1}\ \alpha(1-\tau_1)-\tau_2\left(\frac{1}{n_{k+1}^{*}}-1+\alpha\right)\Big]}{(1+\sigma)(d-s)(1+h)-d}\right\}^{\frac{1}{1+\sigma}}}; \tag{19}$$

and

$$\begin{aligned} \Theta(n_k) \equiv\ & (d-s)(1+\sigma)d^{\sigma} \\ & \left\{\frac{(1-n_k)^{\alpha-1}\left[\alpha(1-\tau_1)-\tau_2\left(\frac{1}{n_k}-1+\alpha\right)\right]}{(1+\sigma)(d-s)(1+h)-d}\right\}^{\frac{\sigma}{1+\sigma}} \end{aligned} \tag{20}$$

As in Aghion and Howitt's model, equation (18) enables us to determine the amount of labour employed in the science sector in era k as function of the labour employed in the successive technological era. Unlike in Aghion and Howitt's model, however, the relation between n_k and n_{k+1} is not univocal. Indeed, while $\Theta(n_k)$ - the marginal costs that derives from investing human resources in research activity- is always increasing in n_k,the function $\Psi(n_{k+1})$ - the marginal benefits- is shaped as an inverted U, with a first trait increasing and then decreasing. An increase in the number of researchers has an ambigous effect on the benefits. In fact, increasing the number of scientists on the one hand reduces the monetary reward obtainable from innovation and the period during which it lasts, while on the other it increases the peer recognition and the prestige obtainable from the innovation. Given that: $\frac{\partial\Theta(n_k)}{\partial n_k} \neq 0$, we can apply the implicit function theorem and define the difference equation that sinthesizes the economy dynamics:

$$n_{k+1} = \Gamma(n_k).$$

A steady state equilibrium is defined as a value of n such that $n = \Gamma(n)$. From equation (20) it is straightforward to verify that the marginal costs deriving from research are always increasing and the function $\Theta(n_k)$ has two asymptotes:

$$\lim_{n_k \to 0} \Theta(n_k) = -\infty; \lim_{n_k \to 1} \Theta(n_k) = +\infty.$$

Moreover, $\Theta(n_k)$ is concave in a first trait and then convex. While the function of marginal benefits $\Psi(n_{k+1})$ is in a first trait increasing and then decreasing with $\lim_{n_{k+1} \to 0} \Psi(n_{k+1}) = \frac{\theta\gamma\tau_1}{r} > 0$.

This implies that equation $n_{k+1} = \Gamma(n_k)$ may be characterized by either one steady state equilibrium or three steady states equilibria, of which two stable and one unstable.

More precisely we have the following results:

Proposition 2 *If there is a fixed component in the total reward of scientist* ($\tau_2 > 0$)*, there always exists a positive number of workers that in steady state equilibrium are employed in science sector. If social prestige deriving from scientific discoveries* (βP_0) *is sufficiently high and* $\frac{\theta\gamma\tau_1}{r}$ *is sufficiently low, there may be three steady states two stable and one unstable. Otherwise only one steady state equilibrium exists. A unique equilibrium is also a stationary solution of* $n_{k+1} = \Gamma(n_k)$ *if prestige does not affect researchers preferences.*

Proposition 2 states that the presence of a fixed salary to scientists is sufficient to rule out the possible existence of a no-growth trap where there is no science sector. While if the monetary reward is too low and prestige is high enough, the model dynamics can show multiple steady state equilibria. In this case, the economy dynamics could converge to different steady states, one in which a large share of employment in the scientific sector makes social prestige high and high incentives attract workers in basic research; the other, that may characterise low developed economies, in which the scientific sector has lower dimension due to less monetary incentives and low social prestige. Multiple steady states are a more likely outcome of the model when social prestige enters preferences with increasing importance.

If the role of social prestige in scientists preferences is not significant then multiple steady states may disappear and the economy may be characterized by only one steady state balanced growth path.

In order to derive the effects of some relevant parameters on the steady state value of scientist employment, we concentrate on the case of a single steady state and we assume that it is stable. After some algebra we are able to state the following proposition:

Proposition 3 *Let us consider the unique stable steady state, n, of $n_{k+1} = \Gamma(n_k)$, then employment in the science sector, n :*

- *increases with an increase of the share of public resources devoted to the sector, τ_1, τ_2;*
- *increases with an increase in importance of prestige of researchers, P_0, β;*
- *decreases with weight of status in the utility function, s, if parameters satisfy this condition: $d \geq \frac{s(\sigma-1)(1+\sigma)(1+h)}{(\sigma-1)(1+\sigma)(1+h)+1}$;*
- *increases with the importance of externalities in basic research, h, if parameters satisfy the following condition $d \geq -\frac{s\sigma(1+h)}{1-\sigma(1+h)}$.*

Some interesting comments can be done on the statements of this proposition. Public policies aimed at the enlargement of the science sector can be realized by collecting more resources form the private sector that will be channelled to higher prizes for scientific discoveries and/or to higher fixed salary of researchers. These kind of policies improve the monetary reward of doing basic research. Strong effects on the size of science sector may derive from changes to the importance of non-monetary components of reward. In fact, it can be easly appreciated the positive effect of social prestige of joining the world of science. This effect accords with both common sense and a large part of sociological literature dealing with science.

The same literature stresses the peculiar features of the scientific community in which the disutility of work is lower than other jobs because of several positive factors. Among the most important is feeling of status and social esteem. According to Proposition 3 the importance of status may reduce the equilibrium dimension of science sector. In fact, we must consider that this effect is direct on effort x, hence increasing effort might induce a lower number of workers to choose basic research.

A similar effect on n is the one that derives from stronger externalities of average scientists effort on the individual probability of success in scientific races. In this case, effort decreases with the parameter h, as always happens with external effects, and the same motivation can be put forward for the same negative effect on n. In both cases externalities mean that individuals do not fully consider benefits that derive from their choices.

4.1 Long run growth and comparative statics

In our economy, production of the final good increases only when an innovation occurs, and this is a probabilistic event. The expected average steady state rate of growth depends on the number of researches employed in science, on the productivity of these workers, on the optimal level of effort and on the magnitude of the technological advance brought about by the innovation. In particular we have:

$$E(g) = E(\ln Y_t - \ln Y_{t-1}) = \theta x(n, s, h, \tau_1, \tau_2)(1+h)n \ln \gamma \tag{21}$$

Parameters that influence the equilibrium number of scientists and their oprimal level of effort, also affect either directly and indirectly the growth rate $E(g)$. Then a simple exercise of comparative statics on equation (21) gives us the effects of these parametes on the size of science sector and on the steady state growth rate. In fact we have:

$$\begin{aligned} \frac{\partial E(g)}{\partial \omega} &= \theta (1+h) \ln \gamma \left\{ \left[\frac{\partial x(n,\omega)}{\partial n} \frac{\partial n}{\partial \omega} + \frac{\partial x(n,\omega)}{\partial \omega} \right] n + x(n,\omega) \frac{\partial n}{\partial \omega} \right\}, \\ where\ \omega &= s, \beta, \tau_1, \tau_2 \end{aligned}$$

and a different formula for h:

$$\frac{\partial E(g)}{\partial h} = \theta \ln \gamma \left\{ \left[\frac{\partial x(n,h)}{\partial n} \frac{\partial n}{\partial h} + \frac{\partial x(n,h)}{\partial h} \right] n(1+h) + (1+h)\, x(n,h) \frac{\partial n}{\partial h} + n x(n,h) \right\},$$

Taking into account comparative statics results concerning effort and n at steady state, we are able to write the following

Proposition 4 *The growth rate of output at steady state increases with parameters β; P_0 that concern prestige in the utility function. The effect of parameters s, h, τ_1, τ_2 on the growth rate depends on the relative strenght of two opposite effects on effort and scientist employment. In particular:*

- *an increase of τ_1, τ_2, h decreases effort but increases employment n;*

  In these cases $E(g)$ is positively affected by parameters if effort does not react too much in comparison with the reaction of employment;

- *an increase of s increases effort but decreases employment.*

  In this case $E(g)$ is positively affected by social status parameter s if it strongly stimulates effort while reducing employment.

This proposition gives us a picture that highlights the role that science sector may have in economic growth. Focus is on rules and norms that prevail in this world and may differ substantially in hystorical esperiences of the most industrialized countries. It also summarises some important results of the paper.

In this model two forces drive the production of new knowledge and economic gowth. One is individual choice of scientists who take part of a complex organization in which incentives derive not only from money income but also from the community rules. The other is the collective choice made by all agents from wich the relative size of science sector derives. The monetary incentive to work in basic research has both an individual and an aggregate dimensions, since the second concerns the distribution of physical resources between the two sectors of the economy.

From the point of view of immaterial incentives we distinguish three components. Social prestige depends on how many peers can evaluate research done by a single scientist. It does not affect effort, but has an influence on the decision to join or not the science sector. If the scientific community is especially generous and efficient in awarding prestige, the science sector will be greater and economic growth stronger.

A different kind of social inteaction is captured by the search for status and conformity. This effect concerns effort that scientists put in their job in comparison with effort of the others and it provides a motivation for individual researchers. The point is that by increasing effort, conformity increases also disutility of work in science and may have a negative influence on employment in science.

Externalities of average effort of scientists affect the individual probability of obtaining a new finding and represent the third context effect in science sector. As usual, externalities in production lower the individual incentive to effort, but cause increasing returns on aggregate activities. This seems to happen also in our model and the result of externalities on growth depends on the relative strenght of these two contrasting effects.

5 Conclusions

This paper represents the first attempt to the modelling of basic research and long run economic growth since work done by Karl Shell in the late sixties. As common in the framework of endogenous growth models, we provide a formalization of the interactions between the scientific sector and the rest of the economy which work both ways. Focus is on the complex organization of basic research that includes both monetary and non monetary incentives. The state organizes production of new knowledge - a public good - with resources taken from the private sector.

Scientists compete each other to get a priority over a discovery and these races are affected by several forms of social interactions. In fact, scientists informal interactions give rise to externalities that hasten discoveries. Also scientists join the science sector to enjoy high social prestige and their behaviour is influenced by a bias towards conformity and status. All these forms of incentive in our model become important determinants of scientist effort and of the size of the sector in comparison with the rest of the economy. Given that science is financed by taxes taken from private firms, output growth and structure of basic research activity jointly determine the dynamics of the economy. This dynamics are not trivial as multiple steady state equilibria can derive from strong effects of social inteactions in science.

Here we set the main lines for the analysis of such an important issue for long run growth that in future work we will further develop in order to deal with welfare issues and public policy.

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