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Social rewards in Science and Economic Growth

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Abstract

In this paper we put forward a model of basic research and long-run economic growth in which the incentives of social reward to scientific work may produce increasing returns and multiple equilibria. The state organizes production of new knowledge - a public good that improves firms' technology - with taxes on the private sector. Scientists compete with one another to attain priority over a discovery and be awarded both a real prize and prestige in the scientific community. Also, scientists derive job motivation from dedication to science which provides social status. Analysis of the model shows, on the one hand, a low equilibrium where the economy is endowed with a small science sector, researchers have high relative income but low prestige, and competition for discoveries is weak. On the other hand, there is a high equilibrium where the economy has a large science sector, scientists obtain for new findings high prestige but lower relative salaries and, as the effect of creative destruction is strong, there is fierce competition among researchers. Comparative statics shows that if the scientific infrastructure is poor, policies that increase the marginal benefits from a discovery have perverse effects, while policies aimed at improving the selection mechanism of researchers work well. The same policies have opposite effects at the high steady state.

Jel codes: O31, Z10, H40, O40

1 Introduction

This paper analyzes the role of the incentive structure in science as a cause of uneven economic growth and multiple equilibria. It develops a model of economic growth which focuses on the organization of the scientific community and explains the huge difference among developed and undeveloped countries with respect to the productivity and the size of the science sector, by focusing in particular on the role played by social rewards in this sector.

International data on size and productivity of science (e.g., Cole and Phelan, 1999; Schofer, 2004) highlight large inequalities across countries, that are even wider than economic inequalities. Table 1 shows the ratio between active researchers and the population, the number of most cited articles per researcher[1] and the real GDP per capita for a sample of 88 countries in 1987. Descriptive statistics highlight striking inequalities across countries with respect to both science and the economy. In fact, the huge distance between maximum and minimum values of per capita GDP is even greater in the case of the share of scientists in the population and also for their productivity. This snapshot is confirmed by the coefficient of variation since the two indicators of science assume values double or triple the value of the same statistic for GDP per capita.

Table 1. Descriptive statistics on GDP per capita and Science indicators of 88 countries. Year 1987.

	Min.	Max.	Average	Coeff. of variation
Real GDP per capita, US $	336	22300	6931.8	0.823
Science researchers per million population	0.002	2.76	0.44	1.537
Highly cited articles per res.	0	80	5.21	2.437

Source: Penn World Tables; Cole and Phelan (1999).

The international distribution of research scientists and real GDP per capita is further elucidated by figures 1-3 which show the country distribution of the three variables. The comparison between scientific and economic indicators of development suggests that in the world economic inequality is shaped by two clubs of countries with high and low per capita income, while in the case of the scientific infrastructure a large number of the low income countries show quite trivial figures that sharply contrast with those of a small club with an important scientific production.

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[1]Data are from Cole and Phelan, 1999, who define active research scientists as "any individual who has recently published one or more papers in a journal included in the Science Citation Index", and most cited articles are defined as articles with more than 40 citations.

Another feature of this sector pointed out by empirical literature is the presence of increasing returns. Cole and Phelan (1999), for example, find a correlation of 0.86 between the number of research scientists per capita and the average number of highly cited articles per scientist for 21 industrialized countries in the year 1987. Figure 4 presents a plot of these variables that confirms the positive relation between them. Recently, Aizenman and Noy (2006) estimated a nonlinear model of the number of major prizes awarded to researchers in ten countries with respect to population and real GDP in the period 1901-2005, the latter being considered a proxy of the amount of resources invested in research. The estimated relation increases at an increasing rate if GDP exceeds a certain threshold. They interpret this result as evidence for increasing returns in the science sector. Even more direct confirmation of the presence of increasing returns in scientific production at country level comes from Carillo, Papagni and Capitanio (2006). This paper contains an econometric analysis of articles per scientist in 4 fields of seven advanced countries in the period 1988-2001. Estimates confirm the findings of Aizenman and Noy (2006) on the existence of increasing returns to scale in all fields analyzed if the science sector exceeds a threshold level.

The presence of increasing returns is able to explain the marked difference between the size and the productivity of science sector of the various countries. However, in the literature there is no a clear analysis of the mechanism which generates them. Our hypothesis is that increasing returns and the inequality among countries in the science sector originate from the institution of open science (David, 1988) which is based on a sophisticated self-reinforcing code of conduct. This code gives rise to a system of rewards that assigns an important role to social rewards such as social prestige and reputation among peers. We think that the way in which scientists acquire reputation and social prestige is able to account for increasing returns and international differences in scientific infrastructures.

The organization of science and its norms of conduct have greatly characterized the development of science in Western countries and can be considered one of the main causes of their economic growth. This hypothesis is largely supported by the literature on the economic history of developed countries. In fact, several historians (Rosenberg and Birdzell,1986; 1990; Bekar and Lipsey, 2001; and Mokyr, 2005) maintain that one of the most important features that distinguishes the most industrialized countries from the rest is their scientific infrastructure. Mokyr (2005) argues extensively that the economic miracle of the Western world can be ascribed in a significant part to the affirmation of science as an institution with an increased ability to

investigate the secrets of nature[2]. This efficiency is principally due to the creation of institutions to host and remunerate scientists together with the increasing specialization of research and the emergence of norms within the scientific community which regulate its activity[3].

Sociological literature has investigated behavioral rules and norms that prevail in the academic world (e.g., Merton, 1957; Ben-David, 1981; Stephan and Levin, 1992). These were mainly analyzed by Merton (1957) and labelled by Ziman (1994) with the acronym CUDOS. The first norm is communalism, by which a researcher identifies with the community of scientists. The second norm is universalism, by which the scientific community is open to all persons of competence regardless of their personal attributes. Two further norms are disinterest and originality by which only the first discoverer of new knowledge obtains a reward. This method of assignation of the reward makes scientific production a "winner takes all" contest and gives scientists powerful incentives to innovate because rewards invariably accrue to those who discover things first (Merton, 1957; Dasgupta and David, 1994). The last norm is scepticism, by which all contributors are subject to critical analysis.

By the interplay of all these norms a particular incentive structure derives which has a multidimensional nature (David, 1988). This contains both real rewards, such as wages, monetary prizes, etc., and non-real (or social) rewards, such as social prestige, higher reputation among colleagues, eponymy[4], etc. More particularly, social reward takes two main forms according to the source from which it derives: one is recognition in terms of high prestige in the scientific community that derives from important publications and innovations; the second is *dedication to research* that depends on psychological characteristics of individuals and on cultural features.

The model shows a nonlinear relation between the benefits deriving from

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[2]The influence of scientific advances on technological innovation and the productivity of economic systems has also been the subject of applied literature for a number of years. The studies by Mansfield (1991, 1995), which are based on surveys of firms' opinions, show the importance of scientific advances for innovation in products and processes, while Adams (1990) estimates the contribution of scientific knowledge to productivity growth in 18 manufacturing sectors. In his paper he finds clear evidence for the relevance of scientific production by measuring it with publications in the scientific fields closest to the sector's technology from the 1930s.

[3]The nineteenth century also saw the birth of prestigious journals which collected and disseminated the results of scientific inquiry. Since then, peer reviewing of articles has allowed objective quality assessment of the products of research and enabled scientists to receive recognition from society in terms of income and prestige (Merton, 1957).

[4]This is the practice of affixing the name of a scientist to all or part of what he/she has discovered, as with the Copernican system etc. (Merton 1957). This is one of the greatest forms of recognition since one's name is immortalized by being attached to an idea.

being a scientist and the size of the science sector that derives from the interplay of two main dynamic forces with opposite sign: the positive one is due to social prestige, positively linked to the size of basic research; the negative one is due to the "priority rule" and to the "creative destruction" effect. From such a nonlinear dynamic model a rich variety of equilibrium outcomes derive. In particular, when the amount of resources invested in research is low and social reward is high, two locally stable steady-states emerge which seem to provide a suitable account of the nexus between science and growth in low income countries and in the most industrialized economies. The picture that emerges shows, on the one hand, an economy endowed with a small science sector where researchers put a low level of effort into research activity and competition for discoveries is weak; on the other hand, an economy with a large science sector and rapid knowledge advancement. In this ideal state of equilibrium, the scientific community rewards members who obtain new findings with high prestige and is characterized by fierce competition among researchers.

Multiple equilibria emerge mainly because of the presence of social rewards. The low equilibrium seems to describe a kind of poverty trap because both the productivity of scientists and growth rate are low and such equilibrium is selected when the science sector and, hence, the economy is at a low level of development. Comparative static results allow us to further characterize this equilibrium as a case of poverty trap since marginal increases in real resources invested in research may have perverse effects on growth by further reducing the scientists' productivity. Only policies aimed at strengthening the social reward deriving from dedication to science, for example, by improving the selection mechanism of the science sector, seem to work well. At the high growth steady state, instead, policies that increase social and real benefits deriving from a new discovery have positive effects on the scientists' productivity, while strengthening the social reward given to scientists only for their dedication to science may have perverse effects on the size of the science sector.

A further result of great interest is that the equilibrium incentive structure depends on the type of equilibrium which prevails, since in the low equilibrium scientists receive a salary which is high when compared with the salary of other workers in the economy, but receive low international prestige, while in the high equilibrium scientists, though highly productive, obtain a lower relative salary but a higher international prestige. This result finds several, albeit indirect, empirical confirmations. Horsby, Martin and Woodburne (2005) show that in several countries (Australia, UK, Canada) there is significant evidence for the relative decline in academic salaries. Stevens (2004) finds that academic salaries in the US and UK, two of the most pro-

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ductive countries in basic research, are lower than the salaries of comparable skilled workers. Ong and Mitchell (2000), by comparing academic salaries within a selected group of English-speaking countries,[5] find that real academic salaries are higher in Hong Kong and Singapore than in the developed countries. Our results may give a possible explanation for this empirical evidence on relative salary of academics even if on this point further empirical analysis is required.

Our paper relates to different strands of literature. One is the Schumpeterian growth theory (e.g., Romer, 1990; Aghion and Howitt, 1992; Grossman and Helpman, 1991), which draws heavily on the microeconomic literature on industrial innovation. More similar to our approach are models of "General Purpose Technology" (Helpman, 1998) that deal with radical changes in technologies that improve production possibilities in a wide range of sectors, which should certainly be associated with advances occurring in the science sector. However, none of these models investigate the sector of basic research taking account of the organization of science that is implicitly assumed exogenous to the economy. In this regard, in the economic growth literature, an exception is Karl Shell (1967, 1969), who proposes a theory of economic growth in which basic research is endogenous. In this model, the state collects resources from the activities of private agents in order to finance basic research, which produces knowledge, a public input to the private sector. Shell investigates the dynamics of such a model economy, but he does not deal with the reward system of the basic research sector as we do.

An important strand of the literature deals with the effects of social reward on economic growth. Most of these studies (e. g., Cole, Mailath and Postlewaite, 1992; Corneo and Jeanne, 2001; Cooper, Garcia-Penalosa and Funk, 2001) investigate social status in terms of agent's concern for relative ranking in wealth and consumption. Cole, Mailath and Postlewaite (1992) argue how such an enlargement of growth theory is able to produce multiple equilibria. Fershtman, Murphy and Weiss (1996) apply this framework to occupational status defined as the comparison between the average human capital of members of a group with respect to average human capital of members of other groups. The present paper is complementary to this strand of the literature since it recognizes the paramount role of social rewards in the scientific production (Fershtman, Murphy and Weiss, 1996; Howitt, 2000) and investigates its implications for economic growth.

In spite of scant growth theory dealing with basic research, economists (Arrow, 1962; Nelson 1959) have long concerned themselves with the world

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[5]Gross salary data are for 1997 and the sample of countries includes Australia, Britain, Canada, Hong Kong, New Zealand, Singapore, South Africa and US.

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; Dasgupta and David, 1987; 1994). Recently, a number of theoretical analyses have shown the substantial differences between the activities of basic research and those of technological innovation. Carraro and Siniscalco (2003) analyze the race between public and private research units for a discovery with potential economic application under the hypothesis of knowledge externalities. Aghion, Dewatripont and Stein (2005) introduce creative freedom, a form of non-real incentive, in a model of scientific research. Comparing academic and private firm organizations - where research has an economic focus - they show that relying on academic organizations in the early stages and on private firms in later stages of research is socially optimal. Lazear (1997) investigates award schemes in basic research contests with a model of overlapping generations of heterogeneous agents and uncertain discoveries. He finds that less able researchers apply less effort than more able ones, and other results concerning the efficiency of various aspects of award schemes.

Dasgupta and David (1987; 1994) constructed a highly general theoretical framework for the analysis 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 and because of the full disclosure rule adopted by researchers when they obtain new results. The 'quest for priority' produces a strong motivation in researchers and 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. In our model we build the microeconomics of science along such main lines, but we place it in a general equilibrium model of economic growth by obtaining an explanation for the broad differences in the science sector among different countries.

The paper is organized as follows. In the second section we present the model. In the third section we analyze the model's equilibrium solution and the implied economic dynamics. Some comparative-statics results are discussed in section 4. Conclusions follow in section 5.

2 The model

2.1 Basic assumptions

In this section we present a model of endogenous growth that follows the framework of neo-Schumpeterian models (Aghion-Howitt, 1992). The pro-

duction side of the economy is made up by two sectors: science and consumption goods production. There is no capital and the only inputs to production are knowledge and workers.

In the model time is continuous and we distinguish calendar time, t, and the state of knowledge that is indexed by k. The economy is populated by a continuum of individuals, of measure 1, who can find employment in one of the two sectors: $l_{t,k}$ work in a competitive sector that produces a consumption good $c_{t,k}$; while $n_{t,k}$ are employed in a basic research sector which produces knowledge $R_{t,k}$ used in the production of the final good. Manufacturing firms are owned by all agents in the economy, and labor and credit markets are perfectly competitive. The state owns and organizes the science sector.

Each individual has an infinite life-span and we assume that every agent derives utility from consumption, from social prestige and suffers a loss of utility from the effort applied to his/her job. Formally the instantaneous utility function is given by:

$$u_{i,t,k} = c_{t,k} + P_{i,t,k} - D_{i,t,k}, \qquad (1)$$

where index i indicates where the agent works: $i = S$ in the case of research and $i = y$ for good production; $c_{t,k}$ stands for consumption, $P_{i,t,k}$ denotes social prestige and $D_{i,t,k}$ is the disutility of effort.

The intertemporal preference rate, $r > 0$, is constant and in equilibrium coincides with the rate of interest at which firms collect savings.

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

$$Y_{t,k} = R_{t,k} l_{t,k}^{\alpha} Z^{1-\alpha} \qquad (2)$$

with $0 < \alpha < 1$, where $R_{t,k}$ is a technological parameter which measures the productivity of the basic knowledge freely available in the technological era k, and Z is an input available with fixed supply that in the following we normalize to 1.

In this economy, innovation is made of new knowledge, R_{k+1}, that is produced in the science sector and increases the productivity of final good workers by a constant parameter $\gamma > 1$. That is to say, we assume that:

$$R_k = R_0 \gamma^k \qquad (3)$$

Consequently k denotes both the state of basic knowledge and the technological era that comes to an end with a scientific discovery[6].

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[6]Since any variable that defines the economy, and therefore the choices made by the agents, remains constant during each technological era, henceforth we simplify the notation by omitting the time index t when it is not indispensable.

2.2 The science sector

The science sector in this economy produces new basic knowledge which is a public good freely available for the production of the final good. The research firm is made up by one scientist. The occurrence of new basic knowledge is uncertain and the probability of success for each agent follows a Poisson distribution whose parameter depends on the effort of the researcher:

$$\theta(x_k) = \theta x_k \tag{4}$$

where x_k is the effort and $\theta > 0$ is a productivity parameter. We also assume that discoveries are independent events across individuals and the aggregate arrival rate is given by:

$$\Theta(n_k x_k) = \theta n_k x_k. \tag{5}$$

2.2.1 The reward system of the science sector

The reward system is a distinguishing characteristic of the academic world. This system rests on the high value attached by scientists to the priority of discovery. As Robert Merton (1957) pointed out, science is an institution which defines originality as a "supreme value" and makes recognition of one's originality a major concern. As a consequence of this norm, researchers compete to be the first to produce a scientific advancement and get a reward from the scientific community. In other words, the scientific sector is a kind of "winner takes all" contest where the first to obtain the innovation gets the whole prize. However, the rule of priority is not the only source of scientist's reward since the latter derives also from the simple running of the research activity even if no innovation occurs.

Another important characteristic of the reward system in science is its multidimensional nature: it usually consists of real reward, often funded by the state, but also of social reward assigned by peers. In the following we will deal with each specific form of reward.

Social reward Many sociologists of science (Merton, 1973; Fox, 1983) have pointed out that social reward is the most substantial part of scientists' total reward and is one of the main factors leading scientists to do research.

A reason that might explain the importance of such a system of scientists' reward may lie in the need to solve problems posed by externalities which arise in research activity (Weiss and Fershtman, 1998). Indeed, given that exclusion from the use of basic knowledge is not feasible, the rule of priority can be an efficient way to reward the producer of it with high social esteem

which requires no direct transfer of resources. The scientist may enjoy this social appreciation and be motivated by it even if he receives a lower salary as a result.

The recognition that scientists obtain, however, is not public acclaim, but rather recognition from their peers[7] which usually takes the forms of citation of their work, the respect of one's colleagues, honorific awards, titles etc.[8]. As noted by Coleman (1990), to establish one's social status the opinion of peers is far more valuable then those of other members of society, since it rests principally on a consensus within a group. This is even more true in the case of scientists, who consider the recognition of their peers highly valuable, while underestimating the opinion of other social groups[9].

The prime motive for which a scientist obtains recognition is for contributing to the advancement of science as judged by experts in the field. However, as Gaston (1978) has pointed out, scientific races, unlike many other races, do not award second and third prizes and assign recognition and fame only to the first to make a discovery. As a result, scientists are obsessed with establishing who has "reached the pinnacle first"[10].

In order to capture these features of scientists' social reward, we assume that this in part is awarded only when a new find occurs. Such prestige is an increasing function of the size of the research sector and the importance of the new discovery. Formally:

$$P_{k+1} = P_0 R_{k+1} n_{k+1}^{\beta} \tag{6}$$

where: $0 < \beta < 1$, $P_0 > 0$ is a constant parameter, and R_{k+1} here captures the importance of the scientific discovery. Hence, according to equation (6), the prestige of a researcher increases as his scientific community becomes larger, but at a decreasing rate.

Although the professional prestige deriving from being an innovator is the principal social reward for a scientist, it is not the only social reward. There are in fact some cultural and psychological characteristics that are valued for their own sake and are enough to keep many scientists working hard at

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[7]Charles Darwin once said, "My love of natural science....has been much aided by the ambition to be esteemed by my fellow naturalists" cit. in Merton, 1957).

[8]The greatest form of recognition is eponymy, the practice of one's name being given to one's own discovery like Boyle's law, the Copernican system, the Cobb-Douglas production function.

[9]As a matter of fact, David Raup (1986) coined the phrase "saganization" to describe the loss of professional reputation that scientists (such as Carl Sagan) suffer after receiving continued mass media attention.

[10]Robert Merton (1957) amply showed how frequent and "hard" are disputes over priority in the history of science.

their research. Among these there is "dedication to science", which finds its 'raison d'etre' in the rules which govern the institution of 'open science', which include the idea that science is a mission to which one devotes oneself[11].

The degree of a scientist's dedication to science contributes to the formation of his reputation, especially in contexts where scientists are a group of highly motivated workers. Scientists who work in environments where there is a strong "science ethos" attach considerable social esteem to colleagues who put a high level of effort into their job and devote themselves wholeheartedly to the advancement of science[12].

In order to consider this dimension of the social reward, which links psychological attitudes and group norms, we hypothesize that devotion to science interacts with the capacity to bear a high level of effort by reducing the disutility deriving from it[13]. This reduction is not direct, but it happens only if there is a gain in reputation, which occurs when a researcher employs a higher than average level of effort.

Formally, the cost of effort will be:

$$D(x_k, \overline{x}_k) = R_k \left[dx_k - s(x_k - \overline{x}_k) \right]^{1+\sigma} \tag{7}$$

with $\sigma > 0$ and $(d-s) > 0$[14]. Where $\overline{x}_k$ is the average effort of the researchers' group, d and σ are two parameters which capture the disutility deriving from effort, while parameter s denotes the reduction in cost deriving from status effect.

Real reward In addition to social rewards, scientists find incentives from real rewards too. These often consist of higher salary, monetary awards, royalties, consulting and speaking fees, which can be considered as prizes for

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[11]Some sociologists of science attribute this scientists' behaviour to the presence of an "inner compulsion" which exists even in the absence of external reward. Indeed, this approach has been called the "sacred spark" theory (Cole and Cole, 1973). In a similar vein, Mary Frank Fox (1983), a sociologist of science, notes that "productive scientists, and eminent scientists especially, are a strongly motivated group of researchers...and have the stamina or the capacity to work hard and persist in the pursuit of long-range goals" (1983, p. 287).

[12]Crane (1965) reports that the social environment (college, department, etc.) is crucial in determining norms, values, attitudes and style of work of scientists.

[13]This hypothesis is confirmed by empirical data on scientists (e.g. Cole and Cole, 1967), which suggests that in general they are highly absorbed, committed and strongly identified with their work and are able to work hard and to persist in a line of research even if the results are uncertain and long-term (see also Aghion, Dewatripoint and Stein, 2005).

[14]This assumption assures that social esteem is not so high as to make the utility function convex (i.e. to make $D(x_k, \overline{x}_k) < 0$).

new finds. There is substantial evidence that scientists' income is related to their productivity. Fulton and Trow (1974), for example, in their study of the academic world in the 1970s concluded that publications "sharply enhance scientists' changes of high salary and earnings outside the universities". Diamond (1986), in his study on mathematicians employed at Berkley, found salary to be positively related to productivity, while Tuckman (1976) found the same relation between publications and financial awards for academic engineering and physics.

Nevertheless, the scientist's income also includes a component that is not strictly related to success in research[15]. In order to capture these important characteristics of scientists' incentive schemes, we assume that each researcher receives a real prize m_{k+1} if he/she produces new knowledge and a fixed salary F_k, just for entering the science sector.

Total reward To summarize the above arguments we argue that total benefits coming from a new find in each instant are given by the real reward (m_{k+1}) plus the social reward (P_{k+1}), both gained when new knowledge is produced and therefore enjoyed in the period that follows k during which research has been carried out. Moreover, we assume that both prizes will last until new knowledge and a new technology appear on the scene. Formally, the total expected rewards in terms of utility that derives from being awarded priority on a discovery is the following:

$$V_{k+1} = \theta(x_k) \int_{t_0}^{\infty} e^{-[r+\theta n_{k+1}(x_{k+1})](t-t_0)} (m_{k+1} + P_{k+1}) dt \qquad (8)$$

The agents' utility function equation (1) implies that in every time period consumption is financed by income. Hence, the expected intertemporal flow of utility that derives from employment in the research sector is given by:

$$U_{S,k} = \int_{t_0}^{\infty} e^{-[r+\theta n_k x_k](t-t_0)} \left[V_{k+1} + F_k - D(x_k, \overline{x}_k) \right] dt = \frac{V_{k+1} + F_k - D(x_k, \overline{x}_k)}{r + n_k \theta x_k}$$

$$(9)$$

2.3 The consumption good sector

In the consumption good sector there is no social prestige attached to this type of work. To simplify the algebra, we assume that the disutility of work

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[15]Often this salary is connected with some other activity not directly linked to research (for example teaching).

is constant and normalize it to zero. Hence, workers in this sector derive utility from consumption only and their expected intertemporal utility is:

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

where w_k is the wage net of taxes.

Workers in the consumption sector receive technology from academic research at no cost, but they pay taxes on wages that the state uses to finance basic research. Considering the production function (2) and the hypothesis of perfect competition, profit maximization yields wages in the consumption good sector given by:

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

where $\tau_k \in (0,1)$ is the tax rate.

2.4 The public sector

To finance production of knowledge by the research sector, the state levies taxes on the consumption sector. To simplify the analysis, we assume that wages of workers in the consumption good sector are taxed according to a flat rate:

$$T_k = \tau_k \alpha Y_k, \tag{12}$$

Our hypothesis on scientists' real reward implies that the public expenditure for the science sector is made of two components: the amount of real income awarded only to those who win a scientific discovery contest, and the fixed real income that does not depend on the outcome of scientific races.

Hence, the state's budget constraint is:

$$m_k + F_k n_k = \tau_k \alpha Y_k. \tag{13}$$

Given tax revenues, the state applies the following simple rule to assign these resources to the two forms of real reward of scientists:

$$m_k = \tau_1 \alpha Y_k, \tag{14}$$

$$F_k = \tau_2 \alpha Y_k, \tag{15}$$

with $\tau_1 \in (0,1)$ and $\tau_2 \in (0,1)$. Hence, $\tau_k = \tau_1 + n_k \tau_2$, where τ_1 and $n_k \tau_2$ represent the shares of private income that go to finance respectively the prize of scientific races and the fixed salary of researchers.

3 Equilibrium dynamics of the model economy

3.1 Equilibrium

Equilibrium in this model economy is defined by both the optimal level of effort that each scientist puts into the research activity and 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 value of the total expected benefits deriving from doing research. We assume that a scientist does not adopt a strategic behavior, such that he/she does not consider the effect of his/her effort on the arrival rate of discoveries in the economy. In this case, maximization of the total benefits gives rise to the following first order equilibrium condition:

$$\frac{\theta(m_{k+1} + P_{k+1})}{r + n_{k+1}\theta\overline{x}_{k+1}} - (d-s)(1+\sigma)R_k\left[dx_{k_t} - s(x_k - \overline{x}_k)\right]^\sigma = 0. \qquad (16)$$

According to equation (16), each researcher chooses the optimal value of effort by equating the expected discounted marginal benefit of one more unit of effort to the marginal disutility that derives from effort. The optimal choice of effort depends on n_{k+1}, the size of the science sector.

Since individuals can choose to participate in the labor 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. From equations (9) and (10) we have the following equilibrium condition for the labor market:

$$V_{k+1} + F_k - R_k\left[dx_{k_t} - s(x_k - \overline{x}_k)\right]^{1+\sigma} = w_k \qquad (17)$$

Given that individuals are homogeneous, equilibrium will be symmetric, which implies that $x_k = \overline{x}_k$. Finally, since the labor market is always in equilibrium we have:

$$n_k + l_k = 1. \qquad (18)$$

3.2 Dynamics

The analysis of dynamic equilibrium derives from the last three conditions. By solving this system we obtain the following implicit difference equation in the variable n_k:

$$\Psi(n_{k+1}) = \Omega(n_k) \qquad (19)$$

where

$$\Psi(n_{k+1}) \equiv \frac{\theta\gamma\left[\alpha\tau_1(1 - n_{k+1})^\alpha + P_0 n_{k+1}^\beta\right]}{r + \theta n_{k+1}\left(1 - n_{k+1}\right)^{\frac{\alpha-1}{1+\sigma}} D^{\frac{1}{1+\sigma}}};$$

and

$$\Omega(n_k) \equiv (d - s)(1 + \sigma)d^\sigma \left(1 - n_k\right)^{\frac{(\alpha-1)\sigma}{1+\sigma}} D^{\frac{\sigma}{1+\sigma}},$$

with $D = \frac{\alpha(1-\tau_1-\tau_2)}{d^\sigma[(1+\sigma)(d-s)-d]}$.

Equation (19) shows how equilibrium dynamics of the model can be represented by a difference equation in n_k only. In fact, from equations (16), (17) and (18) a monotone increasing function of scientific effort with respect to employment can be derived:

$$x_k = \left(1 - n_k\right)^{\frac{\alpha-1}{1+\sigma}} D^{\frac{1}{1+\sigma}}, \tag{20}$$

where x_k assumes a positive value if $D \geq 0$, which is the case if $s < \frac{d\sigma}{(1+\sigma)}$, a condition that hereafter we assume.

The two functions $\Psi(n_{k+1})$ and $\Omega(n_k)$ can be considered respectively the marginal benefits and the marginal costs derived from being a scientist. The shape of both functions depends on the peculiar structure of incentives that we introduced, and in order to study the dynamics of the model, we need complete characterization of both functions, that we summarize in the following lemma.

Lemma The function $\Psi(n_{k+1})$, defined for $n_{k+1} \in [0, 1)$, assumes nonnegative values and is continuous. It is shaped like an inverted U with a first branch increasing and then decreasing. In the increasing branch, the second derivative is negative. Moreover, $\Psi(n_{k+1})$ takes the following two limit values:

$$\lim_{n_{k+1}\to 0} \Psi(n_{k+1}) = \frac{\alpha\theta\gamma\tau_1}{r};$$
$$\lim_{n_{k+1}\to 1} \Psi(n_{k+1}) = 0.$$

The function $\Omega(n_k)$, defined for $n \in [0, 1)$, assumes positive values and is continuous. It is monotone increasing and convex in n_k, and takes limit values:

$$\lim_{n_k\to 0} \Omega(n_k) = (d - s)(1 + \sigma)d^\sigma D^{\frac{\sigma}{1+\sigma}};$$
$$\lim_{n_k\to 1} \Omega(n_k) = +\infty.$$

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Proof: *See appendix.*

As might be expected, the peculiar structure of incentives in science greatly affects the relation between benefits and size of the research sector. In fact, marginal benefits of research depend on the number of future scientists substantially because of two effects with opposite sign. On the one hand, an increasing number of future researchers reduces the real reward obtainable from a new find and the period during which it lasts (creative-destruction effect). On the other hand, an enlarged sector has the effect of increasing prestige obtainable from a discovery (prestige effect). It can be seen that, as n increases starting from low values, the prestige effect initially dominates over creative destruction, making the curve $\Psi(n_{k+1})$ increasing. Subsequently, the latter prevails over the former making the curve decreasing.

The function of marginal cost of research is always increasing in n_k because of the positive effect of n_k on the workers' wage in the consumption sector which is the alternative sector.

From the proof of the lemma it can be verified that $\frac{\partial \Omega(n_k)}{\partial n_k} \neq 0$. Hence, we can apply the implicit function theorem to equation (19) and derive the difference equation:

$$n_k = \Gamma(n_{k+1}). \tag{21}$$

which summarizes the dynamics of equilibrium of the economy under the assumption of perfect foresight[16]. In fact, we define a dynamic equilibrium with perfect foresight as an infinite sequence of scientists' employment $\{n_0, n_1, .n_k...\}$ and scientists' effort $\{x_0, x_1, ..x_k...\}$ that satisfy equations (19) and (20).

From the lemma, it seems clear that equation (21) has an inverse U shape, as figure 5 shows. The difference equation can be characterized by one or two rest points (figure 5), and it can intersect the 45° line both when the curve is increasing and when it is decreasing. Of course, the two curves may not intersect at all, and in this case equilibrium implies nil research and economic growth.

Also, apart from stationary points, the difference equation (21) should allow rich dynamics (e.g. cycles, see Grandmont, 1985; Medio and Raines, 2006). However, we restrict our investigation to steady states because they represent equilibria that contain many of the interesting results of the model. A steady state is defined as the value of n such that $n = \Gamma(n)$. Stability properties of such stationary points will be analyzed in terms of their local forward perfect foresight dynamics. We summarize the cases that we investigate in the following proposition:

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[16]Since $\frac{\partial \Theta^x(x_k)}{\partial x_k} \neq 0$ also holds, a similar difference equation in x_k can be defined: $x_k = \Gamma^x(x_{k+1})$.

Proposition 1 *The difference equation $n_k = \Gamma(n_{k+1})$ can have one or two rest points according to the cases:*

1) If $\frac{\alpha\theta\gamma\tau_1}{r} > (d-s)(1+\sigma)d^\sigma D^{\frac{\sigma}{1+\sigma}}$, then the system has one rest point n^*, which is locally stable in the forward dynamics if it occurs in the decreasing section of the $\Gamma(n)$ curve and the condition $\Psi_n(n^*) + \Omega_n(n^*) < 0$ holds. In this case n_k converges to n^* non-monotonically.

2) If $\frac{\alpha\theta\gamma\tau_1}{r} < (d-s)(1+\sigma)d^\sigma D^{\frac{\sigma}{1+\sigma}}$, then the system has two rest points: n^l, n^h. n^l occurs in the increasing section of the $\Gamma(n)$ curve and is locally stable in the forward dynamics. n^h is locally stable in the forward dynamics if it occurs in the decreasing section of the $\Gamma(n)$ curve and the condition $\Psi_n(n^h) + \Omega_n(n^h) < 0$ holds. While convergence to n^l is monotone, that towards n^h is non-monotone.

3) The two rest points are characterized by the following relations: $n^h > n^l$ and $x^h > x^l$, where x^h, x^l stand for the values of effort implied by equation (20) at steady states[17].

Proof. In appendix. ■

In the first case of proposition 1 there is one stable equilibrium which occurs when the growth potential of the science sector is completely exploited. In fact, in this context, the steady state will be locally stable only if it occurs when the relationship between n_{k+1} and n_k becomes negative and, hence, it occurs when the prestige effect, although it has contributed to the development of the sector by raising the marginal benefits in the first stages, becomes so weak that it does not counterbalance the creative destruction effect. A necessary condition for the emergence of this equilibrium is $\Psi(0) > \Omega(0)$, which is verified for high values of τ_1, τ_2. Hence, if real reward parameters are high, it is more likely that only one equilibrium will emerge.

The second case, which seems the most interesting outcome of the model, is characterized by the existence of multiple equilibria. A necessary condition for the emergence of this case is $\Psi(0) < \Omega(0)$, which is more likely to occur when real rewards parameters τ_1, τ_2 are low and when the 'inner' status parameter s is high. Furthermore, this result derives not only from the above condition, but also from the non-monotonic shape of the marginal benefits curve which derives from social prestige awarded by the scientific community to the winner of a race[18].

Hence the 'rat race effect' introduced in agents' preferences may contribute to the emergence of two equilibria: equilibrium n^l, characterized by low

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[17]The monotone increasing relation between n and x implies that corresponding to the stationary equilibria n^l, n^h there are two steady states x^h, x^l with the same stability properties.

[18]This type of social prestige is captured by parameters P_0 and β .

values of n and x, which occurs when marginal benefits are increasing, hence when the science sector has still unexploited growth potential; and equilibrium n^h, with high values of both n and x, which occurs in the decreasing section of the marginal benefits curve, hence when the science sector has completely exploited its growth potentiality. This latter rest point has the same qualitative characteristics as the rest point that emerges in the case of the unique equilibrium, hence we will refer below to both n^h, x^h and n^*, x^* with the notation n^h, x^h. The two types of steady states (n^h and n^l) differ also in other respects. By considering the ratio of average real income of researchers to workers' wage:

$$\frac{\frac{m}{n} + F}{w} = \frac{\left(\frac{\tau_1}{n} + \tau_2\right)(1 - n)}{(1 - \tau_1 - n\tau_2)},$$

we see that it is a decreasing function of n. This implies that, at equilibrium n^l , the relative[19] real income of scientists is high, while the social prestige is comparatively low with respect to equilibrium n^h. Hence the two types of equilibria differ in their incentive structure: when the science sector is small, prestige plays a minor role in determining the amount of resources invested in research, while when the science sector is well-developed, social prestige is very important and real incentives play a less substantial role.

As regards reputation deriving from dedication to science, this is more important in the low equilibrium since, given the low level of average effort, it is less costly to obtain this kind of reputation.

In order to complete the characterization of the model at steady states we have to focus on the growth rate of aggregate output. Of course, growth proceeds over time according to a stochastic process with leaps in scientific and technological knowledge. At steady states the expected growth rate of goods production may be derived as follows:

$$g \equiv E(\ln Y_t - \ln Y_{t-1}) = \ln \gamma \theta x n. \tag{22}$$

According to equation (22), the growth rate depends positively on the number of researchers and on their level of effort. Hence the two types of equilibria can also be distinguished by the growth rate: low at (n^l, x^l) and high at (n^h, x^h).

The low growth equilibrium (n^l, x^l) seems to describe a kind of low-development trap characterized by a small research sector with growth potential not completely exploited. In this economy scientists have low productivity and receive a relatively high salary and have low international prestige. A high share of the labor force is involved in goods production and there is scant

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[19]In the sense that it is relative with respect to the wages of workers in goods production.

investment in rapid knowledge advances. The opposite picture derives from the model at the high stationary equilibrium. This describes an economy with a large academic community, whose incentive structure shows high social prestige awarded to scientists for their discoveries and real incentives - both m_k and F_k - significant in absolute terms, albeit low in relative terms. The science sector is very productive and can transfer with a fast pace new knowledge to the sector of goods production which becomes very efficient. In this ideal state of equilibrium, creative destruction is strong, hence fierce competition accelerates new discoveries and shortens the time during which prizes are enjoyed.

4 Comparative Statics

In the previous section we underlined the differences in the two types of steady state equilibria. Such differences look even greater in this section where we analyze the reactions of endogenous variables to changes in principal parameters at steady states.

Consistent with the previous discussion of steady states, we concentrate first on the case of low growth equilibrium. Comparative statics results are summarized in the following:

Proposition 2 *Let us consider the case where the stable stationary equilibrium occurs in the increasing section of the $\Gamma(n)$ curve (n^l, x^l equilibrium);*

1) positive changes in parameters P_0, β, τ_1, and τ_2 have negative effects on the number of researchers, on the level of effort and on the average growth rate of real output;

2) positive changes in parameter s have positive effects on the number of researchers, on the level of effort and on the average growth rate.
Proof. *In appendix.* ∎

Proposition 2 seems to provide further support for the view of the low growth steady state as a trap, since it shows that in this case even usual policy instruments might fail. Indeed, both improving the science environment with higher prestige awarded to innovative researchers (P_0 and β) and increasing their real rewards (τ_1 and τ_2) have negative effects on both dimensions of the research sector: number of researchers and the level of effort. Inspection of eq. (22), showing the average growth rate of output, reveals that at the low steady state g^l decreases with parameters $P_0, \beta, \tau_1, \tau_2$ but increases with s.

These unusual effects can be explained by considering that at the low stationary equilibrium the marginal benefit curve $\Psi(n_{k+1})$ slopes upward, mainly because higher foreseen employment in science means higher prestige

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from a discovery. A marginal increase in parameters P_0, β, τ_1, τ_2 shifts the curve upward and the same value of marginal benefit at n^l provides the incentive for a smaller number of agents to enter the science sector. Hence $n_{k+1} < n^l$ and the system moves toward a lower steady state.

An increase in parameter s has only positive effects on endogenous variables. This can be explained by the fact that at low n, the average level of effort is low and a researcher could find it easier to employ a higher than average level of effort. This could allow a scientist to attain high social status by maintaining costs low at the same time. As a result, both an increase in the number of scientists and in their level of effort may be obtained.

Quite interestingly, this last result maintains that if the science sector is made up by people with higher "devotion to science", then the economy will succeed in enlarging the sector with researchers that will put higher effort into their jobs. Such a policy will also increase the average growth rate of output. In this respect, we might interpret an increase of the parameter s as a policy that aims to improve the process of selection of scientists by selecting agents with, on average, better psychological attitudes to the work of research. Such a policy is on government agendas in many developing countries.

A different picture of comparative statics effects of parameter changes derives from the model at steady state which occurs in the decreasing section of the marginal benefits curve. The results are summarized in the following:

Proposition 3 *Let us consider comparative statics at high steady state (n^h, x^h). Then:*

1) positive changes in parameters P_o and β have positive effects on the number of researchers, on their level of effort and on the average growth rate of output;

2) positive changes in parameters τ_1 and τ_2 have positive effects on the number of researchers. When condition (2.a): $nx > \frac{\beta r}{\theta(1-\beta)}$, holds, changes in τ_2 have negative effects on effort, and when (2.a) and (2.b): $(1-\alpha) < \frac{\tau_1}{1-\tau_2}$, hold, also τ_1 causes a reduction in effort. In all these cases, the consequences on the average growth rate are indeterminate;

3) positive changes in parameter s decrease the number of researchers and if condition (2.a) holds, the effect on the level of effort is positive. The consequences on the average growth rate are indeterminate.

Proof. In appendix. ∎

Proposition 3 highlights the fact that changes in parameters P_0 and β, specific to the social reward given to the innovator, have a positive impact on both dimensions of the science sector: size and effort, while strengthening

devotion to science reduces the number of people that may join this sector even if it increases their commitment and hence their level of effort.

Different outcomes derive from variations in real rewards parameters, since their increase will raise the number of scientists, but will reduce the level of effort that they sink in research activity. This is probably due to a kind of income effect by which a higher income attracts more people to that profession but reduces their working hours. The lower the parameter β, which captures the gains in social prestige deriving from an innovation, the more probable is this reduction. Hence the prestige reward may reduce the perverse effects on scientist effort deriving from an increase in real reward.

Summing up, in the case of n^h equilibrium, which may emerge both with one equilibrium and with the multiple equilibria case, social reward deriving from innovation strongly contributes to the development of the science sector. Real incentives do not have the same effects since they may increase the number of scientists but at a cost of reducing their effort. The social reward deriving from dedication to science has the same ambiguous effect, with the difference that rises in effort can be obtained at the cost of reducing the number of scientists.

4.1 Simulation of the effects on the growth rate

As regards the average growth rate of output, from Proposition 3 we know that it increases with parameters of prestige (P, β) but nothing can be said concerning the effects of τ_1, τ_2, and s. An answer to the question of indeterminate sign of some comparative statics effects on g^h can be obtained by a simulation of the model, whose results are presented in table 2[20].

Table 2. Simulated effects of parameters τ_1, τ_2, s **on endogenous variables at steady states.**

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[20]We performed model simulations by assuming the following values of parameters: $\theta = 0.15; \gamma = 1.5; \alpha = 0.7; \beta = 0.5; r = 0.1; s = 0.05; \tau_1 = 0.2; \tau_2 = 0.4; \sigma = 0.4; d = 0.6; P = 2.4$. In this case, the model produces two positive rest points that satisfy conditions for local stability.

	n^l	x^l	g^l	n^h	x^h	g^h
$\tau_1 = 0.2$	0.04	1.66	0.004	0.56	1.97	0.068
$\tau_1 = 0.25$	0.02	1.51	0.002	0.68	1.91	0.079
$\tau_1 = 0.3$	0.008	1.35	0.007	0.77	1.86	0.088
$\tau_2 = 0.4$	0.04	1.66	0.004	0.56	1.97	0.068
$\tau_2 = 0.45$	0.033	1.51	0.003	0.66	1.90	0.077
$\tau_2 = 0.5$	0.026	1.35	0.002	0.76	1.83	0.085
$s = 0.05$	0.04	1.66	0.004	0.56	1.97	0.068
$s = 0.06$	0.043	1.77	0.0046	0.52	2.05	0.064
$s = 0.07$	0.046	1.90	0.005	0.46	2.15	0.060

The above results show that at the high equilibrium the two tax rates may have positive effects on growth, while that of the dedication parameter s is negative. Accordingly, at high growth steady state policies aimed at increasing benefits deriving from research can contribute positively to economic growth. This is not the case of policies targeted to improve the methods for the selection of scientists since our simulation results indicate that higher effort is not enough to compensate the shrinking of the scientific community, and a lower growth rate may result.

4.2   Comparison of theoretical results with stylized facts

What does the above analysis suggest? An overview of our results reveals that the incentive structure of science has rather complex effects on the productivity and size of this sector. Moreover, the effectiveness of the different types of rewards depends on the level of development already reached by the sector. For example, social reward deriving from innovation is the only type of reward that allows science to expand in both its dimensions: effort and size. Nevertheless, it may cause multiple equilibria and hence the emergence of a poverty trap equilibrium where it loses its expansive effects. Hence, even if it may strongly contribute to the development of the sector without employing a huge amount of real resources and allow the difficulty of monitoring effort to be overcome, it may be one of the main causes of the sharp inequalities existing in the science sector of the different countries. Also, social reward deriving from dedication to science has ambiguous effects: on the one hand, it is the only effective tool for the expansion of science in the early stages of its development; on the other, it is another cause of multiple equilibria and hence of the emergence of the poverty trap. Finally, real incentives too have ambiguous effects which again depend on the degree of development

reached by the sector. In the high equilibrium they may increase the number of researchers but at the cost of reducing their effort. In the low equilibrium a marginal increase in them may even reduce the size of the sector, whereas a marked increase in their number allows the low equilibrium to be avoided.

This differing effectiveness of rewards on the development of the science sector is widely confirmed in the history of science and in the process of institutionalization of modern academies.

According to some sociologists of science (Merton, 1957 and Box and Cotgrove, 1966), scientists can be classified into three groups: a first group of scientists for whom recognition from innovation is of major importance; a second group of scientists who use their skills instrumentally as a means of achieving non-scientific rewards, and a third group which "..differs from the first group of scientists only in that they do not attach importance to publication but gained their satisfactions from practising science and from recognition of colleagues" (Cotgrove, 1970, p. 4). Box and Cotgrove (1966) and Cotgrove (1970) find empirical evidence that the third group of scientists is more present when the science sector is in the initial stage of its development ('Little Science', Cotgrove, 1970) and they argue that one result of the growth of science is a change in both the kind of person who becomes a scientist and in the role that he/she plays. Such evidence accords with our theoretical results on the low steady state where dedication to work is an important feature of scientists.

In well-developed academies people are attracted mainly by high prestige and pay deriving from being an innovator, but they give less importance to the status deriving from dedication to science[21]. Furthermore our results can explain why in the last few years in the most developed countries there has been a large increment in the number of scientific awards[22], and why this proliferation especially concerns scientific disciplines that are excluded from the established prestigious scientific awards and begins when they become more important (Zuckerman, 1992). This picture is quite consistent with the main features of the high steady state where social prestige that awards innovations is highly effective for enlarging academy.

Another result of our model is the multiplicity of equilibria which seems

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[21]Cotgrove (1970) has noted that "Big science (i.e. a large science community) offers increasing incentives in the shape of pay, status and power. But it may no longer attract mainly those who previously embraced the role of science as a source of personal emotional gratification. Moreover, the pleasure to be bought with higher incomes may seduce the scientists from the monastic devotion to the pursuit of knowledge. (p. 9, 1970). (Italics and phrases in parenthesis are ours).

[22]In North America there are 3000 scentific awards, five times more than thirty years ago (Zuckerman, 1992).

to agree with evidence on the international distribution of science infrastructures that shows persistent and marked differences across countries (e.g., Schofer, 2004; Cole and Phelan, 1999), with a large club of countries with a negligible science sector and a club to which belong very few countries with a large science sector that produces most of the whole world's scientific production.

The low equilibrium that we described may represent countries with some degree of development, but a long way from the technological frontier. As shown in Schofer (2004), several countries in Eastern Europe, Asia and South America have small scientific sectors with productivity far removed from figures displayed by the USA and other industrialized countries. Data reveal that in such economies, a minority of the population works in the academy, and its marginal position in the international scientific community brings about low prestige. The creation of a scientific sector often derives from public policies aiming to reproduce the successful system of education and science in Western countries (Drori, 1993). Such policies often entail that scientists are compensated with high salaries. While high equilibrium seems more suitable to represent economies which are close to the technological frontier and have a well developed science sector (Schofer, 2004). The most successful system of science, that of the USA, seems to fit with the high steady-state (Ben-David, 1980).

The two equilibria may also explain the empirical evidence on the increasing returns in the science sector. Cole and Phelan (1999), for example, in their analysis of data on scientific research of 95 countries in 1987, find a positive relation between the number of scientists per capita and number of highly cited articles per scientist[23], that is a proxy for scientific productivity. Also Aizman and Noy (2006) as well as Carillo, Papagni and Capitanio (2006) find empirical evidence of increasing returns in the science sector after the latter has reached a critical size.

Finally, as regards the differences in relative salaries of scientists in the two equilibria, recent studies of international academic salaries (Horsley, Martin and Woodburne, 2005) provide evidence for declining salaries of university researchers with respect to professionals for Australia, UK and Canada. Also Stevens (2004) finds that salaries of academics are lower than those of comparable workers in the US and UK, while Ong and Mitchell (2000), on comparing Commonwealth countries, find that Hong Kong and Singapore have academic salaries that are higher than those observed in more developed countries.

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[23]The correlation index between the two variables is 0.55 for the whole sample and 0.86 for 24 industrialized countries.

5   Conclusions

In this paper we put forward a model of basic research and long-run economic growth in which the system of incentives to scientific work which heavily relies on social rewards may produce positive feedbacks and increasing returns. We provide a formalization of the interactions between the scientific sector and the rest of the economy which work both ways.

The organization of basic research presents both real and non-real incentives to workers. The state organizes production of new knowledge - a public good that improves firms' technology - with resources taken from the private sector. Scientists compete with one another to attain priority over a discovery and be awarded both a real prize and prestige in the scientific community. Also, scientists derive job motivation from their search for status in the community. The dynamic of the model economy shows that two locally stable stationary equilibria can derive. These equilibria may describe two polar experiences in international economic growth. One is that of low income countries in which science and technology institutions are not well developed or competitive. The other steady state may be referred to the most industrialized countries that are leaders in the search for scientific advancement. Such sharp differences characterize equilibria with respect to the effects of the incentive structure as well. At low development steady state, incentives to marginally enhance real rewards and social prestige linked to innovation have negative effects on growth, while public policy has to rely on better selection of scientists with special dedication to research, the opposite is true at the high steady state.

In this paper we help establish some of the main criteria for analyzing an issue widely acknowledged as really important for long-run growth (e.g., Howitt, 2000). However, some crucial features of modern science still remain unexplored. In our framework the transfer of new knowledge to firms is straightforward, but many empirical studies emphasize the complexity of this transmission. Another issue that has recently come to the fore is the increasing interest of the business sector in basic research and the reverse increasing patenting activity of universities. Further research will address analysis of these phenomena in the context of growth theory.

6   *Appendix*

Proof of the Lemma

By considering the first derivative of the marginal benefits function with respect to n_{k+1}, we have:

$\frac{\partial \Psi(n_{k+1})}{\partial n_{k+1}} \gtreqless 0 \iff \beta P_0 n_{k+1}^{\beta-1} - \tau_1 \alpha^2 (1-n_{k+1})^{\alpha-1} r +$

$-\theta P_0 n_{k+1}^{\beta} x_{k+1} \left\{ 1 - \beta + \frac{1-\alpha}{(1+\sigma)} (1-n_k)^{\frac{(\alpha-1)}{1+\sigma}-1} D^{\frac{1}{1+\sigma}} \right\} +$

$-\frac{\tau_1 \alpha x_{k+1} \theta (1-n_{k+1})^{\alpha-1}}{1+\sigma} [1 + \sigma - n_{k+1}\sigma(1-\alpha)] \gtreqless 0$

This expression is composed of a positive term - the first, which is decreasing in n_{k+1} and for $n_{k+1}\epsilon(0,1)$ assumes values from $+\infty$ to $\beta P_o r$ - and of three other terms, all negative, whose absolute values are increasing in n_{k+1} and tend to $-\infty$ for $n_{k+1} = 1$. This implies that for $n_{k+1}\epsilon(0,1)$ the above expression is first increasing and then decreasing with one stationary point.

To check the concavity of the increasing section of the marginal benefits function, we consider the sign of its second derivative with respect to n_{k+1}. In this respect we have:

$$\frac{\partial^2 \Psi(n_{k+1})}{\partial n_{k+1}^2} \gtreqless 0 \iff$$

$$-\left[(1-\alpha)\alpha^2 \tau_1 (1-n_{k+1})^{\alpha-2} + (1-\beta)\beta P_0 n_{k+1}^{\beta-2} \right] (r + \theta n_{k+1} x_{k+1}) +$$

$$-\left[\alpha \tau_1 (1-n_{k+1})^{\alpha} + P_0 n_{k+1}^{\beta} \right] - 2\theta \frac{x_{k+1} + n_{k+1}\frac{\partial x_{k+1}}{\partial n_{k+1}}}{(r + \theta n_{k+1} x_{k+1})} \frac{\partial \Psi(n_{k+1})}{\partial n_{k+1}} \gtreqless 0$$

This expression is composed by three terms which are all negative. Also the last term is negative in the increasing section of the marginal benefits curve. Hence, we are sure that in this section the second derivative assumes negative values and the curve is concave.

The two limit values of the marginal benefits function can be trivially derived from an inspection of the marginal benefits function.

To check the shape of the marginal costs function, we calculate its first derivative with respect to n_k, which is:

$$\frac{\partial \Omega(n_k)}{\partial n_k} = (d-s) d^{\sigma} \sigma (1-\alpha) (1-n_k)^{\frac{\sigma(\alpha-1)}{1+\sigma}-1} D^{\frac{1}{1+\sigma}}$$

This expression is always positive. Thus the function is increasing in n_k. The second derivative of $\Omega(n_k)$ is given by the following:

$$\frac{\partial^2 \Omega(n_k)}{\partial n_k^2} = (d-s)\, d^\sigma \sigma\, (1-\alpha) \left[\frac{(1-\alpha)\,\sigma}{1+\sigma} + 1\right] (1-n_k)^{\frac{\sigma(\alpha-1)}{1+\sigma}-2} D^{\frac{1}{1+\sigma}}$$

which is always positive. Thus the marginal costs function is convex.

The two limit values of the marginal benefits function can be trivially derived from an inspection of the function.

Proof of Proposition 1

From the implicit function theorem we know that: $\frac{d\Gamma(n_{k+1})}{dn_{k+1}} = \frac{\Psi_n(n_{k+1})}{\Omega_n(n_k)}$, but $\Omega_n(n_k) > 0$, hence: $\frac{d\Gamma(n_{k+1})}{dn_{k+1}} \gtrless 0$ if $\Psi_n(n_{k+1}) \gtrless 0$. This means that as n_{k+1} increases starting from zero, $\Gamma(n_{k+1})$ is increasing and concave till it reaches a maximum, then it is decreasing. It is easy to verify that $\Gamma(n_{k+1})$ crosses the horizontal axis at a positive value of $n_{k+1} < 1$. From the above lemma we know that the difference equation $n_k = \Gamma(n_{k+1})$ has a graph that intersects the vertical axis if $\Psi(0) > \Omega(0)$, i.e. if

$$\frac{\alpha\theta\gamma\tau_1}{r} > (d-s)(1+\sigma)d^\sigma D^{\frac{\sigma}{1+\sigma}}.$$

In this case, if the map intersects the 45° line at the decreasing branch and condition $\Psi_n(n^*) + \Omega_n(n^*) < 0$ holds, then we have $\left|\frac{d\Gamma^{-1}(n)}{dn}\right| < 1$, which is a sufficient condition for the local stability in the forward dynamics of the rest point n^*. The map $\Gamma(n_{k+1})$ intersects the horizontal axis twice if $\Psi(0) > \Omega(0)$, i.e. if

$$\frac{\alpha\theta\gamma\tau_1}{r} < (d-s)(1+\sigma)d^\sigma D^{\frac{\sigma}{1+\sigma}}.$$

Given the shapes of marginal benefits and cost functions, in this case there can be either no intersection at all or two intersections, which identify the two rest points, n^l and n^h with $n^l < n^h$. At the first stationary point n^l both $\Psi(n_{k+1})$ and $\Omega(n_k)$ are increasing and $\Psi_n(n^l) > \Omega_n(n^l)$ holds, hence $\frac{d\Gamma^{-1}(n)}{dn} < 1$, and n^l is locally stable in the forward dynamics. The higher steady state n^h has the same properties as in case 1, and the same arguments apply.

The last statement of the proposition derives from the monotone increasing relation between x and n.

Proof of Proposition 2

Let us define the implicit function which identifies the two steady state equilibria: $F(n) \equiv \Psi(n) - \Omega(n) = 0$. By considering equation (19), this can be rewritten as :

$$F(n) = \frac{\theta\gamma\left[\alpha\tau_1(1-n)^\alpha + P_0 n_l^\beta\right]}{r + \theta n_l\,(1-n)^{\frac{\alpha-1}{1+\sigma}}\,D^{\frac{1}{1+\sigma}}} - (d-s)(1+\sigma)d^\sigma\,(1-n)^{\frac{(\alpha-1)\sigma}{1+\sigma}}\,D^{\frac{\sigma}{1+\sigma}} = 0,$$

with $D = \frac{\alpha(1-\tau_1-\tau_2)}{d^\sigma[(1+\sigma)(d-s)-d]}$.

For the implicit function theorem we have

$$\frac{\partial n^l}{\partial z} = -\frac{\frac{\partial \Psi(n^l)}{\partial z} - \frac{\partial \Omega(n^l)}{\partial z}}{\frac{\partial \Psi(n^l)}{\partial n^l} - \frac{\partial \Omega(n^l)}{\partial n^l}}$$

where $z = \beta, P_0, \tau_1, \tau_2, s$. In the neighborhood of n^l the denominator is positive because of the stability condition, hence $\frac{\partial n^l}{\partial z} \lessgtr 0 \iff \frac{\partial \Psi(n^l)}{\partial z} - \frac{\partial \Omega(n^l)}{\partial z} \gtrless 0$.

For $z = \beta, P_0$, we obtain:
$\frac{\partial \Psi(n^l)}{\partial z} - \frac{\partial \Omega(n^l)}{\partial z} = \frac{\partial \Psi(n^l)}{\partial x}$; this expression, as can be easily checked, is always positive. Then, in an interval around the low equilibrium, an increase in these parameters always has negative effects on the number of researchers.

For $z = \tau_1$, we have:

$$\frac{\partial \Psi(n^l)}{\partial z} - \frac{\partial \Omega(n^l)}{\partial z} = \frac{\theta\gamma\left[r + \theta n^l\,(1-n^l)^{\frac{\alpha-1}{1+\sigma}}\,D^{\frac{1}{1+\sigma}}\right]\alpha\,(1-n^l)^\alpha}{\left[r + \theta n^l\,(1-n^l)^{\frac{\alpha-1}{1+\sigma}}\,D^{\frac{1}{1+\sigma}}\right]^2}+$$

$$+\frac{\left[\alpha\tau_1(1-n^l)^\alpha + P_0 n^l\right]\theta n^l\,(1-n^l)^{\frac{\alpha-1}{1+\sigma}}\,D^{\frac{1}{1+\sigma}-1}\frac{1}{1+\sigma}\frac{\alpha}{d^\sigma[(1+\sigma)(d-s)-d]}}{\left[r + \theta n^l\,(1-n^l)^{\frac{\alpha-1}{1+\sigma}}\,D^{\frac{1}{1+\sigma}}\right]^2}+$$

$$+(d-s)(1+\sigma)d^\sigma\,(1-n^l)^{\frac{(\alpha-1)\sigma}{1+\sigma}}\,D^{\frac{\sigma}{1+\sigma}-1}\frac{\sigma}{1+\sigma}\frac{\alpha}{d^\sigma\,[(1+\sigma)\,(d-s)-d]}.$$

This expression is always positive, hence $\frac{\partial n^l}{\partial \tau_1} < 0$.

For $z = \tau_2$, then:

$$\frac{\partial \Psi(n^l)}{\partial z} - \frac{\partial \Omega(n^l)}{\partial z} =$$

$$\frac{\left[\alpha\tau_1(1-n^l)^\alpha + P_0 n^l\right]\theta n^l\left(1-n^l\right)^{\frac{\alpha-1}{1+\sigma}} D^{\frac{1}{1+\sigma}-1}\frac{1}{1+\sigma}\frac{\alpha}{d^\sigma[(1+\sigma)(d-s)-d]}}{\left[r+\theta n^l\left(1-n^l\right)^{\frac{\alpha-1}{1+\sigma}} D^{\frac{1}{1+\sigma}}\right]^2} +$$

$$+(d-s)(1+\sigma)d^\sigma\left(1-n^l\right)^{\frac{(\alpha-1)\sigma}{1+\sigma}} D^{\frac{\sigma}{1+\sigma}-1}\frac{\sigma}{1+\sigma}\frac{\alpha}{d^\sigma\left[(1+\sigma)(d-s)-d\right]};$$

which is always positive, hence $\frac{\partial n^l}{\partial \tau_2} < 0$.

For $z = s$, then:

$$\frac{\partial\Psi(n^l)}{\partial z} - \frac{\partial\Omega\left(n^l\right)}{\partial z} =$$

$$-\frac{\theta\gamma\left[\alpha\tau_1(1-n^l)^\alpha + P_0 n^l\right]\theta n^l\left(1-n^l\right)^{\frac{\alpha-1}{1+\sigma}} D^{\frac{1}{1+\sigma}-1}\frac{1}{1+\sigma}\frac{\alpha(1-\tau_1-\tau_2)d^\sigma(1+\sigma)}{\{d^\sigma[(1+\sigma)(d-s)-d]\}^2}}{\left[r+\theta n^l\left(1-n^l\right)^{\frac{\alpha-1}{1+\sigma}} D^{\frac{1}{1+\sigma}}\right]^2} -$$

$$-\frac{\sigma\alpha(1-\tau_1-\tau_2)d^{2\sigma}\left(1+\sigma\right)}{\{d^\sigma\left[(1+\sigma)(d-s)-d\right]\}^2} D^{\frac{\sigma}{1+\sigma}-1}\left(1-n^l\right)^{\sigma\left(\frac{\alpha-1}{1+\sigma}\right)}.$$

This expression is always negative, hence $\frac{\partial n^l}{\partial s} > 0$.

As regards the effects on the level of effort, we derive with respect to $z = \{P_0, \beta, \tau_1, \tau_2, s\}$ the following expression:

$$x_k = \left(1-n_k\right)^{\frac{\alpha-1}{1+\sigma}} D^{\frac{1}{1+\sigma}}.$$

For $z = P_0, \beta$, then:

$$\frac{\partial x^l}{\partial z} = \frac{1-\alpha}{1+\sigma}\left(1-n_k\right)^{\frac{\alpha-1}{1+\sigma}-1} D^{\frac{1}{1+\sigma}}\frac{\partial n^l}{\partial z}.$$

The sign of this expression depends on the sign of $\frac{\partial n^l}{\partial z}$, which, for the parameters at hand, is negative.

For $z = \tau_1, \tau_2$, $\frac{\partial x^l}{\partial z} \gtrless 0 \iff \frac{1-\alpha}{1-n^l}\frac{\partial n^l}{\partial z} - \frac{1}{1-\tau_1-\tau_2} \gtrless 0$, given that for the parameters at hand $\frac{\partial n^l}{\partial z} < 0$, this expression is always negative.

For $z = s$, $\frac{\partial x^l}{\partial z} \gtrless 0 \iff \frac{1-\alpha}{1-n^l}\frac{\partial n^l}{\partial z} + \frac{1+\sigma}{[(1+\sigma)(d-s)-d]} \gtrless 0$, which is always positive.

Proof of Proposition 3

This proposition concerns the comparative statics at the high equilibrium and it also holds for the case of unique equilibrium since the same arguments can be applied. Application of the implicit function theorem to the equation $F\left(n^h, z\right) \equiv \Psi(n^h, z) - \Omega\left(n^h, z\right) = 0$ gives:

$$\frac{\partial n^h}{\partial z} = -\frac{\frac{\partial \Psi(n^h)}{\partial x} - \frac{\partial \Omega\left(n^h\right)}{\partial x}}{\frac{\partial \Psi(n^h)}{\partial n^h} - \frac{\partial \Omega\left(n^h\right)}{\partial n^h}}$$

where $z = \beta, P_0, \tau_1, \tau_2, s$.

In an interval around n^h the denominator is negative because of the stability condition. Hence:

$$\frac{\partial n^h}{\partial z} \lessgtr 0 \iff \frac{\partial \Psi(n^h)}{\partial z} - \frac{\partial \Omega\left(n^h\right)}{\partial z} \gtrless 0.$$

This implies that in the n^h equilibrium, changes in the different parameters have the opposite sign with respect to those in the low equilibrium. Hence $\frac{\partial n^h}{\partial z} > 0$ for $z = \{P_0, \beta, \tau_1, \tau_2, s\}$.

To find the effects of changes in the relevant parameters on the level of effort, we rewrite the equilibrium condition as a function of effort. In this case the implicit function which defines the steady states is:

$$\Psi(x^h) - \Omega(x^h) = \frac{\theta\gamma\left[\alpha\tau_1 x^{-\frac{\alpha(1+\sigma)}{1-\alpha}} D^{\frac{\alpha}{1-\alpha}} + P_0\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^\beta\right]}{r + \theta x\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)} +$$

$$-x^\sigma(1+\sigma)d^\sigma\left(d - s\right).$$

and it can be easy to derive:

$$\frac{\partial x^h}{\partial z} = -\frac{\frac{\partial \Psi(n^h)}{\partial x} - \frac{\partial \Omega\left(x^h\right)}{\partial x}}{\frac{\partial \Psi(x^h)}{\partial x^h} - \frac{\partial \Omega x^h}{\partial x^h}},$$

where $z = \beta, P_0, \tau_1, \tau_2, s$.

Close to n^h the denominator of the last equation is negative because of the stability condition. Hence:

$$\frac{\partial x^h}{\partial z} \lessgtr 0 \iff \frac{\partial \Psi(x^h)}{\partial z} - \frac{\partial \Omega\left(x^h\right)}{\partial z} \gtrless 0.$$

For $z = P_0$,

$$\frac{\partial \Psi(x^h)}{\partial z} - \frac{\partial \Omega(x^h)}{\partial z} = \frac{\theta\gamma\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^{\beta}}{\left[r + \theta x\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)\right]^2}, \text{ which is always positive.}$$

For $z = \beta$,

$$\frac{\partial \Psi(x^h)}{\partial z} - \frac{\partial \Omega(x^h)}{\partial z} = \frac{\theta\gamma P_0 \beta \ln\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)}{\left[r + \theta x\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)\right]^2}$$

which is always positive.

For $z = \tau_2$, we have $\frac{\partial \Psi(x^h)}{\partial z} - \frac{\partial \Omega(x^h)}{\partial z} \gtreqless 0$ iff

$$-\gamma\alpha\tau_1 x^{1+\sigma} D^{-1} + \gamma\beta P_0\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^{\beta-1} - \Psi(x^h)x \gtreqless 0.$$

But the last expression is negative if

$$\gamma\beta P_0\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^{\beta-1} - \Psi(x^h)x < 0,$$

which is satisfied if the following condition holds: $nx > \frac{\beta r}{\theta(1-\beta)}$.
For $z = \tau_1$,

$$\frac{\partial \Psi(x^h)}{\partial z} - \frac{\partial \Omega(x^h)}{\partial z} \gtreqless 0 \iff \gamma\alpha x^{1+\sigma} D^{-1}\left[(1-\alpha)(1-\tau_1-\tau_2) - \alpha\tau_1\right] +$$

$$+\gamma\beta P_0\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^{\beta-1} - \Psi(x^h)x \gtreqless 0.$$

The last expression is negative if $\left[(1-\alpha)(1-\tau_1-\tau_2) - \alpha\tau_1\right] < 0$, which is satisfied if $(1-\alpha) < \frac{\tau_1}{1-\tau_2}$, and if

$$\gamma\beta P_0\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^{\beta-1} - \Psi(x^h)x < 0,$$

which is satisfied if the following condition holds: $nx > \frac{\beta r}{\theta(1-\beta)}$.
For $z = s$,

$$\frac{\partial \Psi(x^h)}{\partial z} - \frac{\partial \Omega(x^h)}{\partial z} \gtreqless 0$$

$$\iff$$

$$+\gamma\alpha\tau_1 x^{1+\sigma} D^{-1} - \gamma\beta P_0\left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^{\beta-1} + \Psi(x^h)x \gtreqless 0.$$

The last expression is positive if

$$\gamma \beta P_0 \left(1 - x^{\frac{-(1+\sigma)}{1-\alpha}} D^{\frac{1}{1-\alpha}}\right)^{\beta-1} - \Psi(x^h)x > 0,$$

which is satisfied if the following condition: $nx > \frac{\beta r}{\theta(1-\beta)}$ holds.

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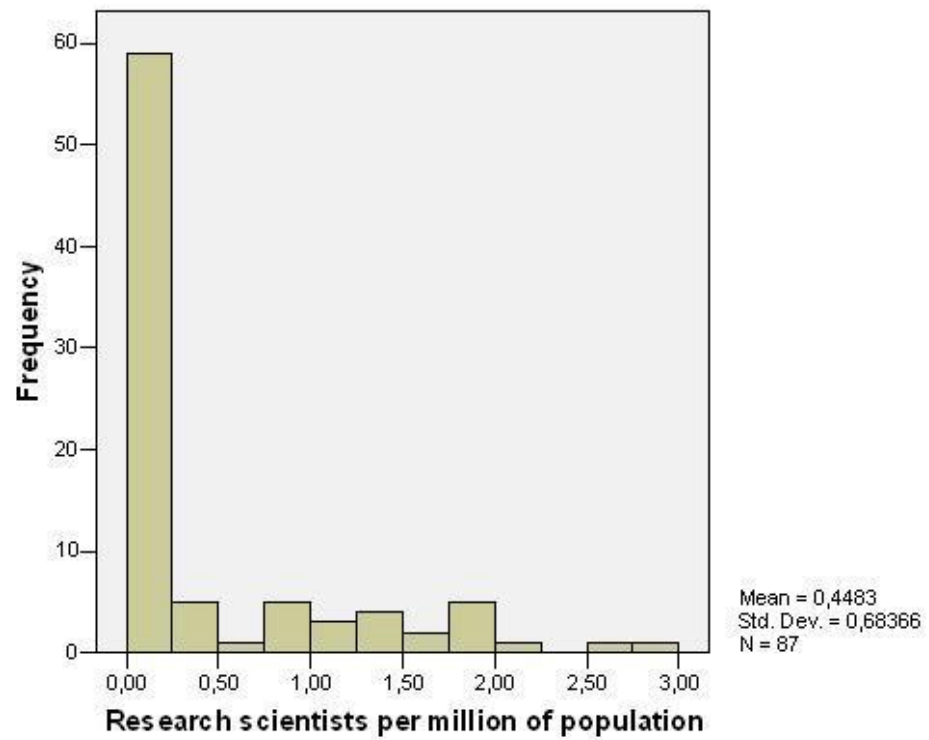
Figure 1. World distribution of scientists per
million of population. Year 1987.
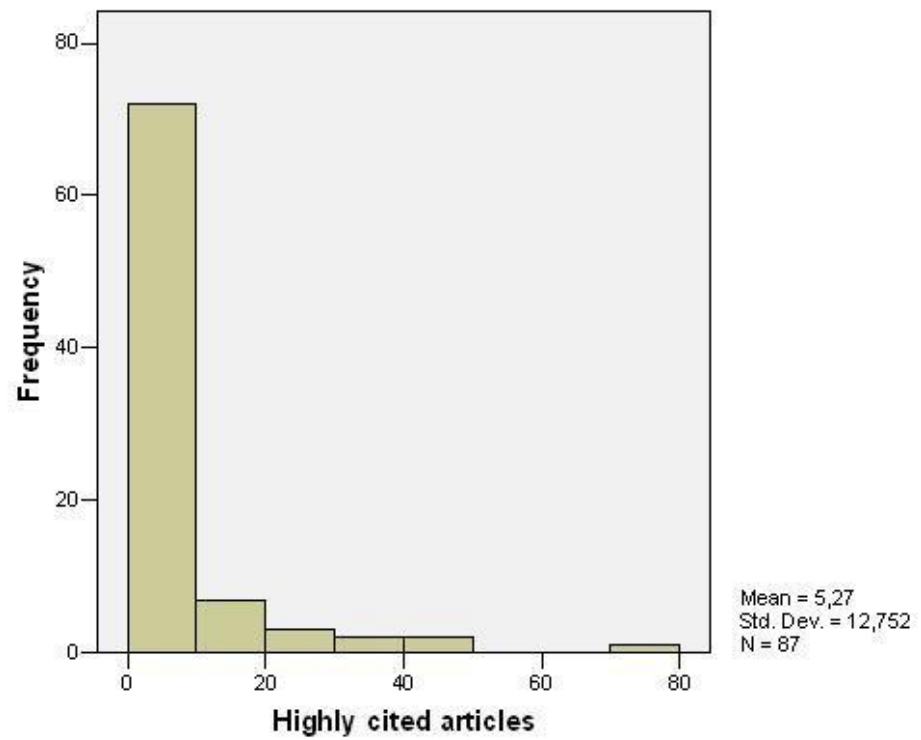
Figure 2. World distribution of articles with more
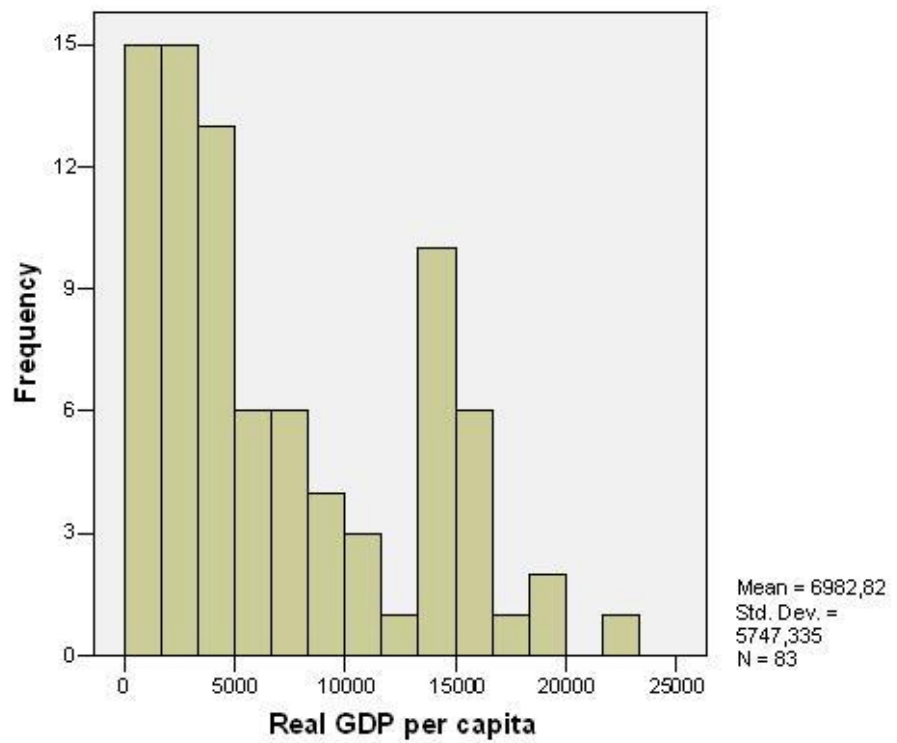than 40 citations. Year 1987.

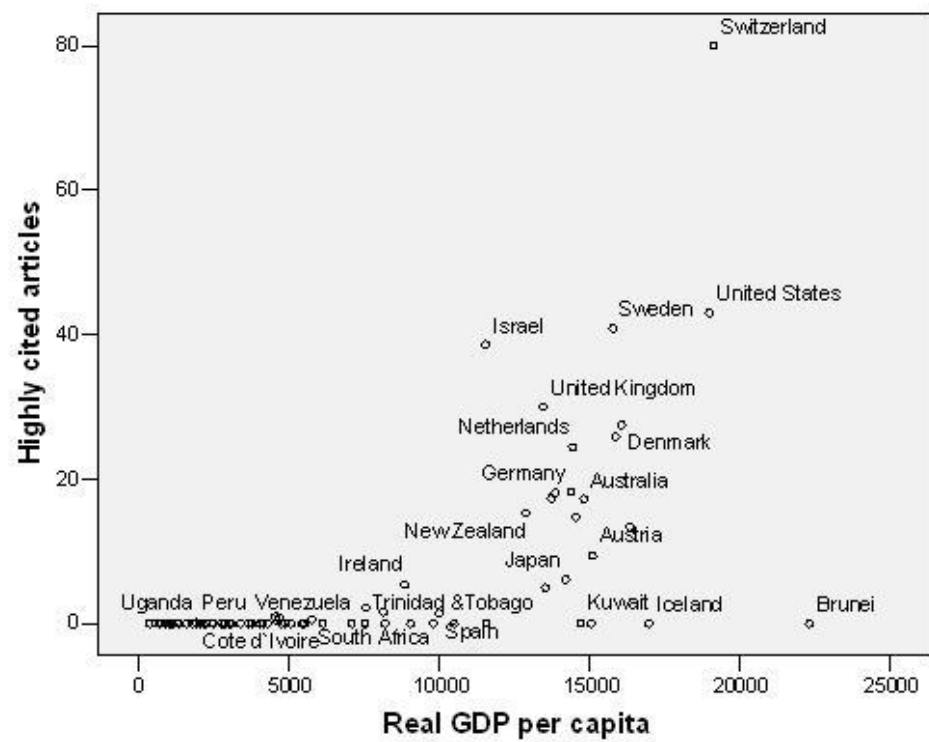Figure 3. World distribution of real GDP per capita.

Year 1987.

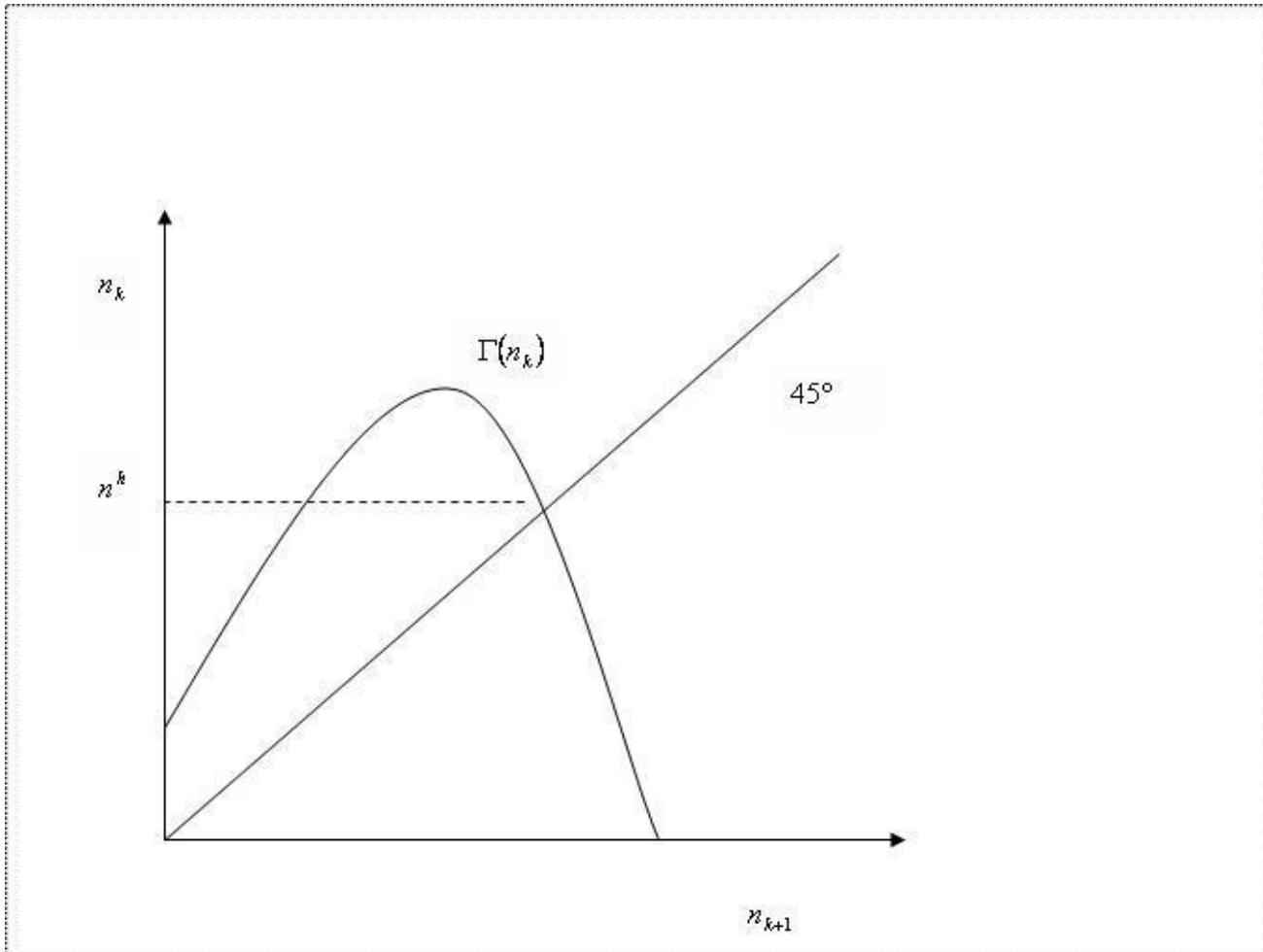Figure 4. Highly cited articles and real GDP per capita in 88 countries. Year 1987.

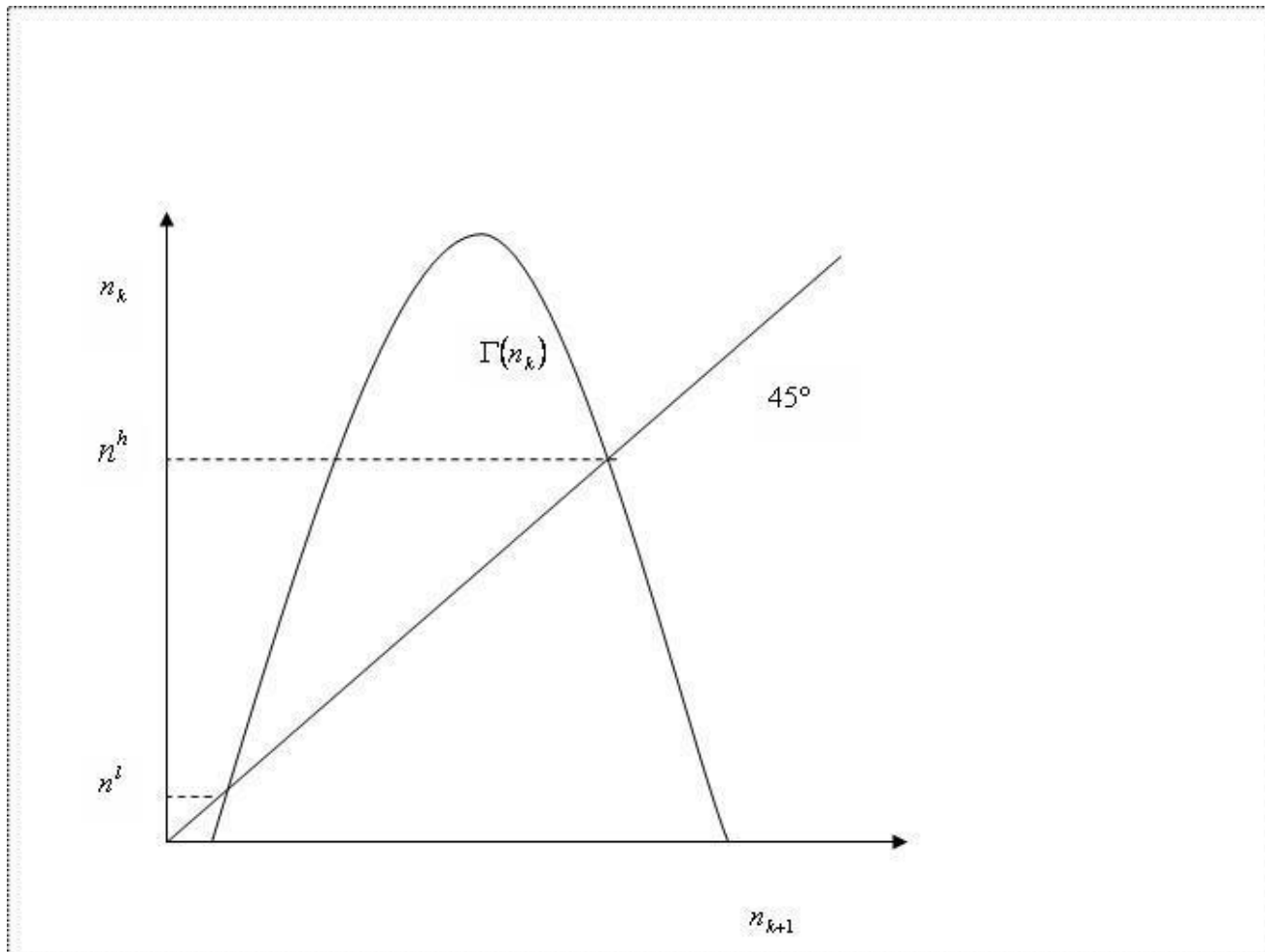Figure 5a. Dynamics of the size of the science sector.

The case of unique equilibrium.

Figure 5b. Dynamics of the size of the science sector.

Multiple equilibria.