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R&D poverty traps

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Abstract: In this paper we show that the R&D effort of a country and its economic growth are highly correlated. In order to analyze this relationship, we study the nature of the researching activity. In particular, we focus on the following characteristics of research: the inherent uncertainty of researching, the existence of a wage premium associated to innovative activities, and moral hazard. Assuming that a higher R&D effort translates into a higher R&D success probability, we show that when the R&D success probability is low, the economy is not willing to bear the risk associated to R&D activities. As a consequence, few researchers are hired and the economy stays in an R&D poverty trap, a situation where the economy is stacked in a low growth environment due to the uncertainty associated with the researching activity. In this situation, the economy grows at a constant rate, independent of the R&D success probability (although it could grow at a higher rate through a higher effort). On the other hand, if the economy increases its R&D effort such that the R&D success probability increases sufficiently, then the risk associated with R&D activities drops and the economy hires more researchers. Consequently, growth does depend on the R&D success probability and technological advancement becomes a driving force of the economy. We show that imperfect information widens this R&D poverty trap. We also show that subsidizing R&D through researchers' hiring increases growth, but it does not increase the likelihood of leaving the R&D poverty trap. Moreover, the subsidy widens the R&D poverty trap..

JEL Codes: O30,O38,O40, O41

Keywords: R&D, poverty trap, growth.

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1 Introduction

Technological advancement has defined our understanding of the economic activity through successive eras of our contemporary history. If modern economic history can be said to have started with the Industrial Revolution, a period of great innovation, we currently live in the Information Age, an era whose existence and evolution is defined by technology. The growing influence of technology on the economic activity justifies a closer look at the mechanisms governing R&D and its impact on the long-term behavior of the economy. Thus, and since the seminal paper of Romer (1990), a vaste literature has focused on R&D as one of the most important engines of growth. This literature has two main, and opposite, branches. On one hand, for some economists as Romer (1990), an economy with few resources devoted to research and, in particular, with few researchers, will grow at low rates. Naturally, having fewer people dedicated to research makes less likely the creation of new products and innovations. Then, the success probability that any researcher has of inventing a new design in any period, or R&D success probability, becomes a crucial element in explaining growth. A higher R&D success probability implies a higher growth rate. On the other hand, for other economists as Jones (1995a), the amount of resources devoted to research or the number of researchers have no effect on growth, at least in the long run, but their growth rates. As a consequence, the R&D success probability has no role in the determination of growth. In this case, a higher R&D success probability implies the same growth rate. Therefore, a question arises naturally: which theory is (mostly) correct?

In view of Figure 1, it seems that there is no correlation between the resources devoted to research and growth.[1] In fact, Jones (1995a) already showed the same results for the number of scientists. In any case, are the total resources devoted to research a good measure of the R&D effort of a country? Figure 2 shows the correlation between the Summary Innovation Index (SII) elaborated by the EU and economic growth. This index gives an overview of aggregate national innovation performance and is a composite indicator of 25 measures ranging from 0 (worst performance) to 1 (best performance).[2,3] From the data,

[1]The same lack of correlation arises with respect to GERD, either in per capita value or only the part made by private sectors, or the time serie for US.

[2]We have normalized the SII to 100 in the figure. Also, we have chosen the year 2003, as it is the only one publicly available.

[3]Alternative measures of R&D effort, like the Global Innovation Index elaborated by the WIPO or the Science, Technology and Industry Index elaborated by the OECD also have problems with the public availability of their data.

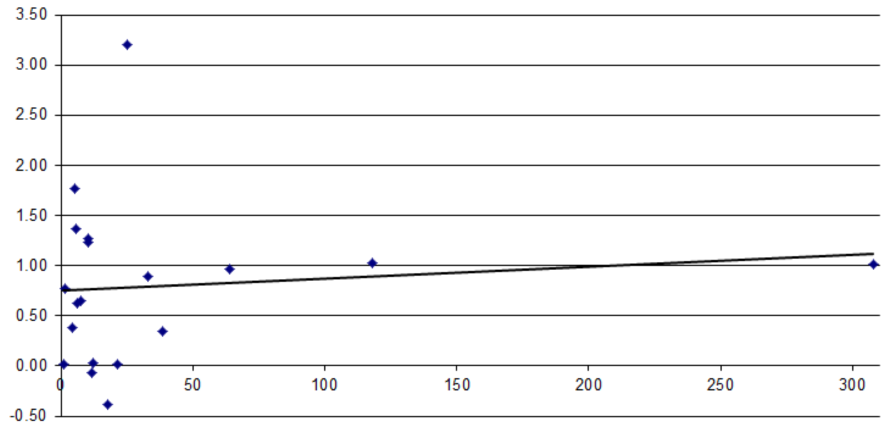

Figure 1: Mean TFP growth (2003-2008) and 2003 Gross Domestic Expenditure on R&D (GERD) in thousands of millions at current PPP (2004 for Switzerland and Australia). Source: OECD. $R^2 = 0.011$ with a correlation of 0.103.

it seems clear that there are some other causes apart from total resources that can explain the relationship between growth and R&D. The goal of this paper is to show that economic growth is heavily connected to the R&D effort of a country. We achieve this goal by exploring the inherent characteristics of the researching activity. In particular, we focus on the following characteristics: the uncertainty of researching, the wage premium associated to innovative activities, and moral hazard. In particular, we assume that a higher R&D effort by a country translates into a higher R&D success probability. We first analyze the case of perfect information: the principal or employer R&D firm observes the researcher's effort. Note that perfect information does not eliminate uncertainty, since we still have a R&D success probability. We show that when this R&D success probability is low, a risk averse economy is not willing to bear the risk associated to R&D activities. Consequently, a small number of researchers are hired and growth does not depend on the R&D success probability or research productivity. But, if for any reason, an economy increases its R&D effort such that the R&D success probability increases sufficiently, then the risk associated to R&D activities falls and the economy hires more researchers. As a consequence, growth does depend on the R&D success probability and technology advancement becomes a driving force of the economy.

Unlike other economic activities dealing with more "physical" goods, with

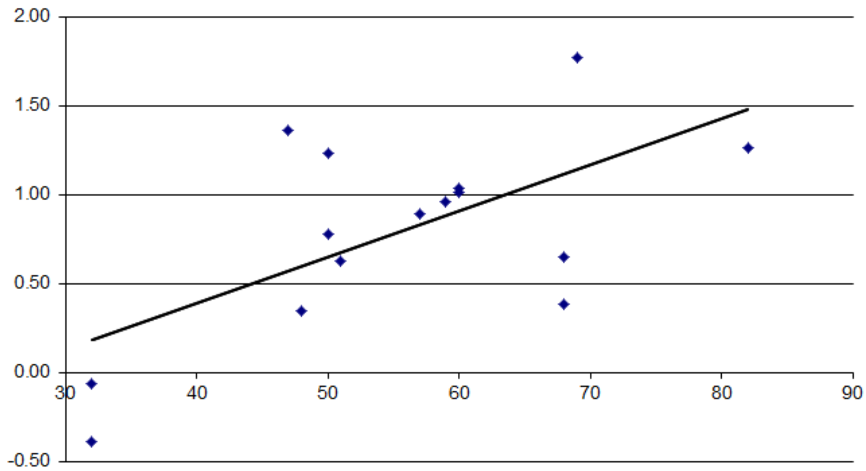

Figure 2: Mean TFP growth (2003-2008) and SII2003. Sources: OECD and European Commission. $R^2 = 0.392$ with a correlation of 0.626.

outputs that can be easily measured and predicted, researching usually involves some degree of uncertainty. Economists are familiar with this reality: study hard to obtain a not-so-good mark, spend days trying to incorporate an idea to a paper unsuccessfully or, on the contrary, have a great idea while watching the R.C.D. Espanyol football team on TV. This uncertainty can be extended to most R&D activities and is incorporated into our economy. We depart from the well-known model of Romer (1990) by having an R&D sector dedicated to create patents for new intermediate goods with researchers that do not invent patents immediately, but merely possess a probability of creating one. This R&D success probability will be higher if the researcher makes an "effort", or "works hard", and will be lower otherwise, what we call "shirking".

But, what is this "effort" in our economy? To understand it, we have to take a look at a well-documented phenomenon: the existence of a wage premium on innovation related sectors over the average sector.[4] There are many explanations for this premium, but we are sticking to the "compensatory theory": being a productive worker in a research-related job usually requires the acquisition of skills through education. That way, the higher salaries would be the reflection of a compensation for this previous effort and the higher productivity of the workers because of this effort. In our economy, we define two levels of effort,

[4]See, for example, Katz and Murphy (1992).

high and low. The high effort makes the workers in the R&D sector to be more productive, so that the R&D success probability becomes higher. The low effort can be considered the default level of effort, the effort of "just working" in any sector of this economy.

That leads us to the last insight, on information. There is no education sector in our economy, so that workers are self-taught. Under this condition, all the workers have ex-ante the same productivity for the principal or employer R&D firm, who cannot verify if the researcher has worked hard or shirked. A problem of moral hazard arises naturally: the employer's profits depend directly on the effort of the worker, but the effort is costly and cannot be observed by the employer, which gives the worker an incentive to shirk. However, as the R&D success probability increases with effort, the result of the researching activity gives some hint on the behavior of the researcher. That opens the possibility for firms to incentive researchers to work hard by offering a higher salary when succeeding, which is more probable when the effort is present, and penalizing them when failing. That also means, however, that the wage premium will be higher when there exists this kind of informational problem, as researchers have to be compensated for both the effort and the uncertainty.

The existence of a principal-agent informational problem where the researcher knows the effort exerted but not the principal who hires her, widens the likelihood of a technological poverty trap: a situation where the economy is stacked in a low growth environment due to the uncertainty associated to the researching activity. This situation arises when the R&D success probability is too low. In this case, no principal is willing to pay the researcher enough so that she exerts the high effort. As a consequence, the economy grows at a constant rate which is independent of the R&D success probability (although it could grow at a higher rate through a higher effort). In order for the principal to be willing to pay the researcher for the high effort, a sufficiently high R&D success probability is needed. In that case, growth depends on the R&D success probability and the economy leaves the R&D poverty trap.

Surprisingly, incentivizing R&D through a subsidy on researchers' hiring increases growth, but it does not increase the likelihood of enforcing the high effort. That is, the subsidy is not able to reduce the R&D success probability that makes the economy to leave the R&D poverty trap. But, once this threshold probability is exceeded, the gap between the high R&D effort growth rate and the low R&D effort growth rate becomes bigger. Moreover, the subsidy widens the R&D poverty trap. Hence, instead of subsidizing R&D through researchers' hiring, a government should implement policies aimed at increasing the R&D effort or success probability. Additionally, two comments must be made. First, any change in the R&D success probability could be due to an increase in total population, human capital or education, population density, or knowledge concentration (marshallian industrial districts), all of them part of the R&D effort of a country. Although Galor and Weil (2000) make technological progress to be directly governed by total population and education, we focus on the relation between technological progress and the R&D success probability. And second, once the R&D poverty trap is left behind, our economy predicts a positive correlation between income and R&D effort.

This paper is related to two branches of macroeconomics: how R&D affects growth, and how effort affects aggregate production. Since we depart from Romer (1990), our economy suffers from absolute scale effects. Certainly, population enhances growth, since more population means more researchers, more designs and higher growth. These scale effects were discredited in Jones (1995a,b), that proposed a modification of the Romer's economy that eliminates the absolute scale effects (but introduce relative scale effects). That way, it is the population growth what enhances growth, although population and production continue to be related. Obviously, since in Jones' model the R&D success probability has no effect on growth, the informational problem has no effect on growth, either. Sánchez-Losada (2014) discusses the causes of absolute and relative scale effects and proposes an alternative modeling. However, even though the presence of scale effects could undermine the global appeal of the results of this paper, our intention is to show the effects of R&D effort, R&D success probabilities and information on growth.

There are few papers in macroeconomics analyzing the effects of effort on aggregate production. An exhaustive analysis can be found in Leamer (1999). He proposes a production function where effort enters as total factor productivity, giving rise to a set of contracts paying for a higher effort. However, this paper has no informational problems, which are incorporated in Acemoglu and Newman (2002) and Bental and Demougin (2006). In both papers, the existence of asymmetric information creates the need for monitoring of the workers' effort by the firms. In the former, monitoring affects the corporate structure of firms, which in turn affects output, while in the latter monitoring affects total factor productivity through effort. To our knowledge, there is no paper analyzing the relationship between asymmetric information and effort, and R&D.

The addition of R&D effort, R&D success probabilities, wage premia and informational problems to the original model of Romer (1990) will no doubt allow us to improve our understanding of the foundations of economic growth. Section 2 outlines our modified version of the Romer's economy with the addition of theses new features. We discuss two variations of the model: a benchmark version with perfect information and a version with imperfect information, so that we can easily distinguish the formal effects of moral hazard. That is the objective of Section 4. In between, Section 3 discusses the role of a subsidy on R&D, while an account of the influence of the other additions (R&D effort, R&D success probabilities and wage premia) are discussed in Section 5. Finally, Section 6 concludes, reflecting on the formal results of the previous sections while making a first approximation to some policy issues that can be extracted from the main conclusions of the model.

2 Perfect information: the benchmark economy

Our framework is a modified overlapping-generations version of the well-known Romer's economy. Even though this model has lost some appeal, after some features of the model were subsequently rebutted, we think that it remains an excellent and tractable framework to analyze the effects of technology on growth. We develop first a benchmark economy with perfect information. The results obtained on this setup will be subsequently compared with those obtained when introducing asymmetric information on the economy: a moral hazard problem in the R&D sector. As many of the features of the model are common with those of the Romer's economy, we move quickly through these and focus on the proposed additions.

There are three sectors in this economy. A competitive research sector uses labor and the existing stock of technology to produce new designs. A monopolistically competitive intermediate goods sector uses these designs and foregone output to produce inputs for a final goods sector. Apart from the intermediate goods, the competitive final goods sector uses labor to produce final output, which can be either consumed or saved. Thus, there are two basic inputs, capital and labor, with their productivities affected by the state of technology. Capital is measured in units of consumption goods. Each individual is endowed with one unit of labor supplied inelastically. We assume constant population L.[5]

Technology A is measured as the number of designs for intermediate goods

[5] Since in Romer (1990) there are scale effects and we follow his model, we need this assumption for a balanced growth path to exist.

in the economy.[6] Therefore, the invention of new designs counts as an increase in A. Technology is advanced by the effort of the L_A researchers working in the R&D sector. Any researcher has a probability δ of inventing a new design in any period t, or R&D success probability, so that this occurrence is a random variable following a Bernoulli distribution of parameter δ. If we assume the work of the researchers at any moment to be independent of each other, the aggregate effort of the L_A researchers is a random variable following a Binomial distribution with parameters (L_A, δ).[7] The average of this variable is $L_A\delta$, so that the evolution of the technology in this economy can be described by the equation $A_{t+1} = A_t + A_t L_A \delta$. That is, the number of designs the next period will be the number of designs this period plus the number of newly invented designs, itself a function of currently existing designs. Hence, the growth rate of technology g_A is

$$\frac{A_{t+1} - A_t}{A_t} = g_A = L_A \delta. \tag{1}$$

Final output Y is produced in a perfectly competitive environment with a combination of intermediate goods and labor L_Y. Intermediate goods are indexed by the integer i and limited by the state of the technology. Therefore, $\{x_i\}_{i=1}^{A}$ is the list of intermediate goods available for a final goods firm. Each final goods firm maximizes profits,[8]

$$L_Y^{\alpha} \left(\sum_{i=1}^{A} {x_i}^{1-\alpha} \right) - w_Y L_Y - \sum_{i=1}^{A} p_i x_i, \tag{2}$$

where the production function is à la Dixit-Stiglitz, w_Y is the wage paid in this sector per unit of labor, and p_i is the price of the intermediate good i. The optimality conditions are

$$w_Y = \alpha L_Y^{\alpha-1} \left(\sum_{i=1}^{A} {x_i}^{1-\alpha} \right), \tag{3}$$

$$p_i = L_Y^{\alpha} (1-\alpha) {x_i}^{-\alpha}. \tag{4}$$

Since workers are employed either in the final goods sector or in the R&D

[6]We omit the time subscript until necessary.

[7]If $X_1, ..., X_n$ are independent, identically distributed random variables, all Bernoulli distributed with success probability ξ, then $Y = \sum_{k=1}^{n} X_k \sim Binomial(n, \xi)$.

[8]The final good price p_Y is normalized to one.

sector, we have

$$L = L_Y + L_A. \tag{5}$$

A producer of an intermediate good purchases a design created on the R&D sector, which confers monopoly power over that particular good. As in Romer (1990), we assume a putty-putty technology, where we need η units of final good to produce 1 unit of intermediate good. The problem faced by each firm i is to maximize the difference between its revenue $p_i x_i$, and its expenses $r\eta x_i$, subject to its inverse demand function (4), where r is the interest rate and there is no depreciation. The optimality condition is

$$p_i = \frac{r\eta}{1-\alpha}, \tag{6}$$

and, then, profits π_i are

$$\pi_i = \alpha p_i x_i. \tag{7}$$

From now on, we will only consider the symmetric case, where all the firms in the intermediate goods sector produce the same quantity x, set the same price p and have the same profits π. Then, we have that

$$\sum_{i=1}^{A} {x_i}^{1-\alpha} = \sum_{i=1}^{A} x^{1-\alpha} = Ax^{1-\alpha}. \tag{8}$$

Individuals live for two periods: in the first period they work and receive a wage w. This salary is allocated between consumption c and savings s. In the second period they are retired, so that their income is the return on savings Rs, where R is the interest factor, which is entirely consumed as d. The individual utility function,

$$U(c, d, E) = \ln c + \beta \ln d - \ln E, \tag{9}$$

where $\beta \in (0, 1)$, captures the idea that individuals derive utility from consumption and disutility from the effort E they have to exert at work. Solving the intertemporal individual problem, we have

$$s = \left(\frac{\beta}{1+\beta}\right) w,\ c = \left(\frac{1}{1+\beta}\right) w,\ d = \left(\frac{\beta}{1+\beta}\right) Rw, \tag{10}$$

and substituting these conditions into equation (9) we obtain the indirect utility function

$$V(w, E, R) = (1+\beta)\ln w - \ln E + \beta \ln R + Z, \tag{11}$$

where Z is a constant.

A firm in the R&D competitive sector maximizes profits $p_A A L_A \delta - w_A L_A$, where w_A is the wage paid in this sector per unit of labor and p_A is the price of a new design. Furthermore, in the R&D sector workers face a decision: they can shirk and apply a low effort E_l normalized to one, $E_l = 1$, which yields an R&D success probability δ_l; or they can work hard and apply a high effort $E_h > E_l$, which yields an R&D success probability $\delta_h > \delta_l$.

Additionally, we assume that working in the final goods sector always requires an effort equal to one. With that, we do not imply that working in the R&D sector is harder than working in the final goods sector, but that being a highly productive worker in the R&D sector requires an extra effort, in terms of education, that working in the final goods sector does not.

With perfect information firms know whether the worker has worked hard or shirked. Therefore, workers will be paid according to the effort they have applied. Moreover, in this setup workers are risk averse, as their utility function is concave with respect to the wage, and firms are risk neutral, as the profit function is linear with respect to income. That means that firms will bear all the inherent risk of the research activity and will completely insure workers by rewarding them regardless of the result of their research.[9]

For the moment, we will assume that firms are interested in extracting the high effort from their workers, although lately we will analyze the conditions under which this assumption holds. To enforce the low effort, firms simply have to offer a salary $w_A^l = w_Y$, so that workers obtain the same utility working in the final goods sector than shirking in the R&D sector, since in both cases workers make the same effort. To enforce the high effort, however, firms need to compensate the worker for the effort.[10] In that case, the optimization problem of a firm trying to make its researchers to work hard will be subject to a participation constraint that reflects this compensation. This restriction expresses that a hard worker in the R&D sector must have at least the same utility than a worker in the final goods sector[11], that is, $V(w_A^h, E_h, R) = V(w_Y, 1, R)$, where w_A^h is the wage paid for the high effort. This restriction can be rewritten as

[9] To shield themselves from the risk, it can be assumed a pooling of the R&D firms, where they are able to issue state-contingent securities. In that way, by holding a diversified portfolio from all the R&D firms in this economy, firms can dispose of any idiosyncratic risk inherent to their own projects.

[10] For an introduction on economics of information, see Macho-Stadler and Pérez-Castrillo (2001).

[11] Since individuals are identical, the labor market clearing condition makes the restriction to bind.

$w_A^h = w_Y \widehat{E}$, where $\widehat{E} = E_h^{\frac{1}{1+\beta}}$. We call $\widehat{E}$ the wage premium of working hard in the R&D sector versus shirking. The problem of the representative R&D firm is

$$Max\ \pi_A^h = p_A A L_A \delta_h - w_A^h L_A$$
$$s.t.\ w_A^h = w_Y \widehat{E} = \alpha L_Y^{\alpha-1} A x^{1-\alpha} \widehat{E}, \tag{12}$$

where we have used equations (3) and (8). Free entry makes profits to be zero, which implies that

$$p_A = \frac{\alpha L_Y^{\alpha-1} x^{1-\alpha} \widehat{E}}{\delta_h}. \tag{13}$$

The price of a new design reflects the incentives of the producers of intermediate goods to acquire it. Following Grossman and Helpman (1991), we can express that, at every moment in time, the instantaneous excess of revenue over the marginal cost must be just sufficient to cover the interest cost on the initial investment in a design. Or, in other words, the price of a design is equal to the present value of the net revenue that a monopolist can extract. In our case, that means $\pi_t / p_{A_t} + \left(p_{A_{t+1}} - p_{A_t}\right) / p_{A_t} = r_t$, which combined with equations (4), (7) and (13), and evaluating in the balanced growth path where $p_{A_{t+1}} = p_{A_t}$, gives

$$L_Y = \frac{\widehat{E}}{\delta_h} \frac{r}{1-\alpha}. \tag{14}$$

And substituting equations (5) and (14) into equation (1) yields

$$g_A = \delta_h L - \frac{\widehat{E} r}{1-\alpha}. \tag{15}$$

We now focus on the behavior of capital K. Because it takes η units of forgone consumption to create one unit of intermediate good, total usage of capital is

$$K = \eta \sum_{i=1}^{A} x_i = \eta A x. \tag{16}$$

Since individuals work in either the final goods sector or the R&D sector, the capital market clearing condition is

$$\left(\frac{\beta}{1+\beta}\right) \left[(L - L_Y) w_{At}^h + L_Y w_{Yt}\right] = L s_t = K_{t+1} + p_{A_t} A_{t+1},$$

where we have used equations (5) and (10). Using the fact that $\pi_A^h = 0$ and equations (4), (6), (12), (14) and (16), in the balanced growth path we have that $p_{A_t}A_{t+1} = K_{t+1}[\alpha/(1-\alpha)]$. Combining these last two equations with equations (3), (4), (6), (8), (12), (14) and (16), we obtain

$$K_{t+1} = \Lambda \left[\delta_h L - \frac{r_t(\widehat{E}-1)}{1-\alpha} \right] K_t,$$

where $\Lambda = [\alpha\beta/\,(1+\beta)] < 1$. Rewriting this equation gives

$$g_K = \Lambda \left[\delta_h L - \frac{r(\widehat{E}-1)}{1-\alpha} \right] - 1. \tag{17}$$

Finally, substituting the definition of capital in the production function yields $Y = L_Y^{\alpha} A x^{1-\alpha} = (L_Y A)^{\alpha} K^{1-\alpha} \eta^{\alpha-1}$, which tells us that Y, K and A must grow at the same rate in the balanced growth path. Therefore, equations (15) and (17) give

$$g_h = \frac{\Lambda \delta_h L - \widehat{E}}{\widehat{E} - \Lambda(\widehat{E}-1)}, \tag{18}$$

where the subindex h indicates that this is the growth rate of the high R&D effort economy. But firms are not always interested on extracting the high effort from their workers. By comparing profits of R&D firms when they offer a salary $w_A^h = w_Y \widehat{E}$ (so that workers work hard and the R&D success probability is δ_h) and when they offer a salary $w_A^l = w_Y$ (so that workers always shirk and the R&D success probability is δ_l), and noting that by equation (12) we have $\pi_A^h = 0 = p_A A \delta_h - w_Y \widehat{E}$, then R&D firms are interested in the high effort if $\pi_A^h = 0 > \pi_A^l = L_A\,(p_A A \delta_l - w_Y)$, that happens whenever

$$\delta_h > \widetilde{\delta}_h = \delta_l \widehat{E}. \tag{19}$$

That is, R&D firms only want their workers to work hard if the likelihood ratio of inventing a new design δ_h/δ_l is greater than the wage premium $\widehat{E}$. In other words, they are willing to pay for the high effort if the gain in probability derived from working hard is greater than the bonus they have to pay to achieve this high effort. This condition separates the states where R&D firms are interested in making their workers to work hard, so that the growth rate of the economy is g_h, and the states where enforcing the high effort is simply not worthy, so that the wage premium and the effort is 1 and, therefore, the growth rate of the economy is $g_l = \Lambda \delta_l L - 1$.

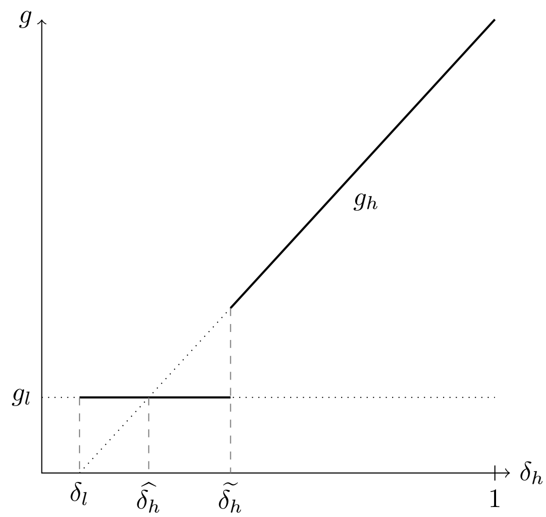

Figure 3: Growth as a function of δ_h

Figure 3 shows these states by depicting the growth rate as a function of δ_h. Note that the growth rates can be negative due to the chosen normalization of the effort. For this reason we assume that $\delta_l > 1/\Lambda L$. Also note that this figure does not show a possible evolution of the economy as δ_h grows, since we are only dealing with the analysis on the balanced growth path.

In order to draw Figure 3, note that $g_h = g_l$ whenever

$$\delta_h = \widehat{\delta}_h = \delta_l[\widehat{E} - \Lambda(\widehat{E} - 1)] + (\widehat{E} - 1)/L. \tag{20}$$

Then, by comparing equations (19) and (20) we have that $\widetilde{\delta}_h > \widehat{\delta}_h$. Figure 3 expresses that if we have two economies, then the economy with the higher δ_h will grow at a higher rate unless both economies are trapped in the area where enforcing the high effort is not worthy. In this area, both economies grow at the same rate g_l. Moreover, we can have the case[12] where although the high R&D effort economy would grow at a higher rate, the market takes the economy to a low growth rate. This situation is what we call a R&D poverty trap, a situation where the economy is stacked in a low growth environment due to the uncertain nature of the researching activity. Moreover, in this case an improvement of δ_h does not guarantee a faster growth rate.

[12] $\delta_h \in (\widehat{\delta}_h, \widetilde{\delta}_h)$.

3 Perfect information: the role of a subsidy on R&D

It is clear from Romer (1990) that a subsidy on R&D enhances growth through an increase in the number of researchers. But does such a subsidy affect the R&D poverty trap? That is, does the subsidy make it more likely to enforce the high effort? Is the subsidy able to reduce the R&D success probability that makes the economy to leave the R&D poverty trap?

Consider a government that subsidizes the hiring of researches through a tax on labor income. Thus, the government gives a proportional subsidy z on R&D wages and sets a proportional tax τ on households' wages. The government budget constraint is

$$[L_A w_A + L_Y w_Y]\,\tau = L_A w_A z. \tag{21}$$

From the intertemporal individual problem, we now have

$$s = \left(\frac{\beta}{1+\beta}\right) w\,(1-\tau)\,,\ c = \left(\frac{1}{1+\beta}\right) w\,(1-\tau)\,,\ d = \left(\frac{\beta}{1+\beta}\right) Rw\,(1-\tau)\,, \tag{22}$$

and substituting them into equation (9) gives the following indirect utility function:

$$V(w,E,R) = (1+\beta)\ln w - \ln E + \beta \ln R + (1+\beta)\ln(1-\tau) + Z,$$

from where we have that the participation constraint remains unchanged and, thus, equation (12) is still valid.

The problem of the representative R&D firm is

$$Max\ \pi_A^h = p_A A L_A \delta_h - w_A^h\,(1-z)\,L_A$$

subject to equation (12). Since free entry makes profits to be zero, then

$$p_A = \frac{\alpha L_Y^{\alpha-1} x^{1-\alpha} \widehat{E}\,(1-z)}{\delta_h}. \tag{23}$$

Substituting this price into the non-arbitrage condition yields

$$L_Y = \frac{\widehat{E}}{\delta_h}\frac{r\,(1-z)}{1-\alpha}. \tag{24}$$

And substituting equations (5) and (24) into equation (1) gives

$$g_A = \delta_h L - \frac{\widehat{E} r\,(1-z)}{1-\alpha}. \tag{25}$$

Using equations (21) and (22), and operating similarly to the previous section, from the capital market clearing condition we have

$$g_K = \Lambda \left(\delta_h L - \frac{r\left[\widehat{E}\,(1-z) - 1\right]}{1-\alpha} \right) - 1. \tag{26}$$

And combining equations (25) and (26) gives

$$g_h^s = \frac{\Lambda \delta_h L - \widehat{E}(1-z)}{\widehat{E}(1-z) - \Lambda[\widehat{E}(1-z) - 1]}, \tag{27}$$

where the superscript s denotes that the growth rate is with a subsidy. When R&D firms are not interested in making their workers to work hard, so that the wage premium and the effort is 1, the growth rate of the economy is $g_l^s = \left[\Lambda \delta_l L - (1-z)\right] / \left[1 - z\,(1-\Lambda)\right]$. Note that $\partial g_h^s / \partial z > 0$ and $\partial g_l^s / \partial z > 0$. Moreover, the slope of g_h^s is bigger than the slope of g_h. Also note that by equation (12) we have $\pi_A^h = 0 = p_A A \delta_h - w_Y \widehat{E}\,(1-z)$, and that R&D firms are interested in the high effort if $\pi_A^h = 0 > \pi_A^l = L_A \left[p_A A \delta_l - w_Y\,(1-z)\right]$, what happens whenever $\delta_h > \widetilde{\delta}_h$. Finally, $g_h^s = g_l^s$ whenever

$$\delta_h = \overline{\delta}_h = \frac{\delta_l \left(\widehat{E}(1-z) - \Lambda[\widehat{E}(1-z) - 1] \right) + (1-z)(\widehat{E} - 1)/L}{1 - z(1-\Lambda)}. \tag{28}$$

Note that $\partial \overline{\delta}_h / \partial z < 0$. Moreover, $\overline{\delta}_h\big|_{z=0} = \widehat{\delta}_h$ and $\overline{\delta}_h\big|_{z=1} = \delta_l$. Figure 4 shows the economy with and without the subsidy. The subsidy increases growth, but it does not increase the likelihood of enforcing the high effort. That is, the subsidy is not able to reduce the R&D success probability that makes the economy to leave the R&D poverty trap. But, once this threshold probability is exceeded, the gap between the high R&D effort growth rate and the low R&D effort growth rate becomes greater. Moreover, the subsidy widens the R&D poverty trap; that is, the values of δ_h for which there is a poverty trap situation.

In view of the results, it is more interesting to wonder if a government can alter either the likelihood ratio of inventing a new design or the wage premium.

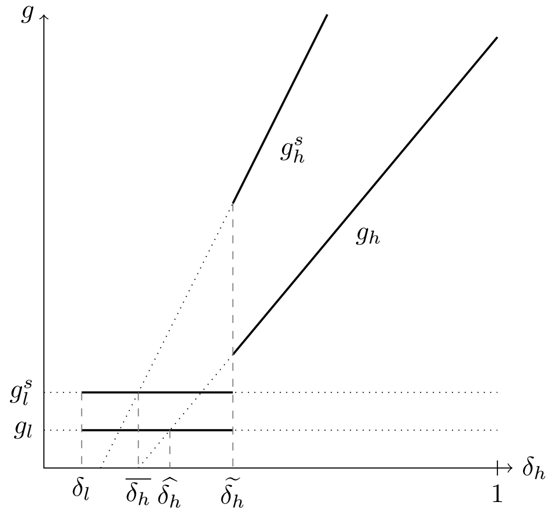

Figure 4: Growth with a subsidy as a function of δ_h

We claim that it is likely that a government can alter both by investing in R&D infrastructures or subsidizing the R&D capital, aspects that are not modeled in this paper. We therefore imply that the R&D success probability δ_h has some degree of endogeneity, and that it may depend on, for example, total population, total number of researchers, or infrastructure like labs, such that any government policy altering one of these variables may change the R&D effort of an economy.

4 Imperfect information and moral hazard

In this section, we modify the benchmark economy by adding imperfect information in the R&D sector. The rest of the economy remains unaltered, so that equations (1) through (11) hold. Now, R&D firms are unable to distinguish if their employees have worked hard or have shirked. The only information firms have is the final result of the researching process: whether a new design has been invented or not. Hence, a problem of moral hazard arises.

If, as in our benchmark economy, R&D firms were to insure completely the researchers by paying them the same salary regardless of the outcome, the researchers would shirk, as the employers cannot observe their effort and there are no consequences for their action. Therefore, if firms are interested in extracting the low effort from the researchers, they just need to pay a salary $w_A^l = w_Y$ regardless of the result, which leads the economy to a growth rate $g_l = \Lambda\delta_l L - 1$. Instead, if firms are interested in extracting the high effort from the researchers, they cannot insure their workers completely and will have to pay them according to the result of their work. If the researcher manages to discover a new design she will be paid a salary w_A^g; otherwise, she will be paid $w_A^b < w_A^g$. This feature adds a new restriction to the problem of the R&D firm. Not only it has to lure the worker from the final goods sector (the participation constraint), but it must also offer an incentive such that the worker prefers working hard to shirking. This new restriction is the incentives constraint. This restriction states that under the two-salaries payment scheme we have described, the expected utility of working hard must equal the expected utility of shirking.[13] Furthermore, now the participation constraint changes slightly to reflect the new payment scheme. Formally, both restrictions are

$$\delta_h V(w_A^g, E_h, R) + (1-\delta_h)V(w_A^b, E_h, R) = V(w_Y, 1, R),$$

$$\delta_h V(w_A^g, E_h, R) + (1-\delta_h)V(w_A^b, E_h, R) = \delta_l V(w_A^g, 1, R) + (1-\delta_l)V(w_A^b, 1, R).$$

Combining both restrictions and using equation (11), we have

$$w_A^g = w_Y \widehat{E}^{\frac{1-\delta_l}{\delta_h-\delta_l}}, \tag{29}$$

$$w_A^b = w_Y \widehat{E}^{\frac{-\delta_l}{\delta_h-\delta_l}}. \tag{30}$$

Now we have two different wage premia, one when the researcher discovers a new design and other (actually, a penalty) when she fails. Therefore, we can define the expected wage premium when the researcher works hard as

$$\widetilde{E} = \delta_h \widehat{E}^{\frac{1-\delta_l}{\delta_h-\delta_l}} + (1-\delta_h)\widehat{E}^{\frac{-\delta_l}{\delta_h-\delta_l}}. \tag{31}$$

The problem of a representative R&D firm is

$$Max\ \pi_A^h = p_A A L_A \delta_h - [\delta_h w_A^g + (1-\delta_h)w_A^b]L_A \tag{32}$$

subject to equations (29) and (30). Free entry implies zero profits. Hence, using

[13]See footnote 11.

equations (3) and (8), we have

$$p_A = \frac{\alpha L_Y^{\alpha-1} x^{1-\alpha} \widetilde{E}}{\delta_h}. \tag{33}$$

This condition is the equivalent to equation (13) but switching from the perfect information wage premium $\widehat{E}$ to the imperfect information expected wage premium $\widetilde{E}$. Replicating the computations of the benchmark economy, in the balanced growth path we have

$$g_h^m = \frac{\Lambda \delta_h L - \widetilde{E}}{\widetilde{E} - \Lambda(\widetilde{E} - 1)}, \tag{34}$$

where the superscript m denotes that the growth rate is with moral hazard. However, R&D firms will not always be interested in extracting the high effort from their employees. Comparing profits when firms use the two-wage scheme and extract the high effort, and when firms use the single salary scheme so that workers shirk, we obtain a condition similar to the perfect information case but with the expected wage premium,[14]

$$\delta_h > \widetilde{\delta}_h^m = \delta_l \widetilde{E}. \tag{35}$$

Figure 5 shows these states. To draw it, we have that $\delta_h = \widehat{\delta}_h^m = \delta_l[\widetilde{E} - \Lambda(\widetilde{E} - 1)] + (\widetilde{E} - 1)/L$ when $g_h^m = g_l$. Noting from Figure 6 that $\widetilde{E} \geq \widehat{E}$, we have that $g_h^m \leq g_h$, and with equality when $\delta_h = 1$. Also note that $\widetilde{\delta}_h^m \geq \widetilde{\delta}_h$ and $\widehat{\delta}_h^m > \widehat{\delta}_h$. The case of imperfect information increases the range of values of δ_h for which the economy falls to a state of low growth due to the fact that exhorting the high effort is not worthy. Therefore, imperfect information widens the R&D poverty trap, so that the excessive uncertainty of the researching activity is aggravated by the imperfect information on the researchers' behavior.

5 Discussion of the results

Now, we can establish a comparative analysis of the effects on growth of changes to the discovery probabilities, the wage premia and the information structure. It is, however, a comparison between stationary states, as we are not discussing the dynamic properties of the model.

[14]Note that since $\widetilde{E}$ depends on δ_h, the exact δ_h satisfying this equation is implicitly defined.

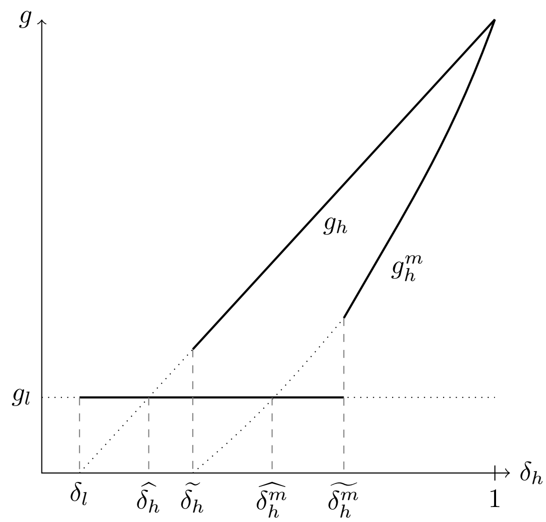

Figure 5: Growth with moral hazard as a function of δ_h

First, it is usually thought that an increase in the R&D success probability when working hard increases the growth rate since a bigger probability means bigger income for the R&D firms and, then, a bigger share of the labor force working in the technological sector, which offers higher salaries and, thus, consumption and production increase. In our paper, however, an economy with a higher R&D success probability does not necessarily experience a higher growth rate. We have shown a situation where enforcing the high effort is not worthy and the economy drops to g_l, which is independent of δ_h. If the economy founds itself in this state, an increase on δ_h will not affect growth, unless it is big enough to move the economy towards the state where R&D firms prefer their researchers to work hard. We have called this situation a technological poverty trap.

Second, an increase in the effort E_h needed to have a higher R&D success probability reduces the growth rate in both the perfect and the imperfect information economies since $\Lambda < 1$. Therefore, a higher E_h always slows growth.

Third, we compare the results obtained in our model with perfect and imperfect information. The main difference between both economies is the wage premium, $\widehat{E}$ and $\widetilde{E}$, so that a comparison between both premia is enough to unveil the effects of imperfect information. We can deduct, from equation (31), that generally the expected premium $\widetilde{E}$ is greater than the premium with perfect information $\widehat{E}$, as Figure 6 shows. This is an intuitive result, as $\widehat{E}$ is merely compensating the high effort of the researcher whereas $\widetilde{E}$, besides, is compensating the risk the researcher has to bear in the imperfect information version.[15] The only situation where both wage premia are equal is when $\delta_h = 1$, that is, when we have perfect information because there is certainty in the result of the researching activity: the researcher always invents a design when working hard.

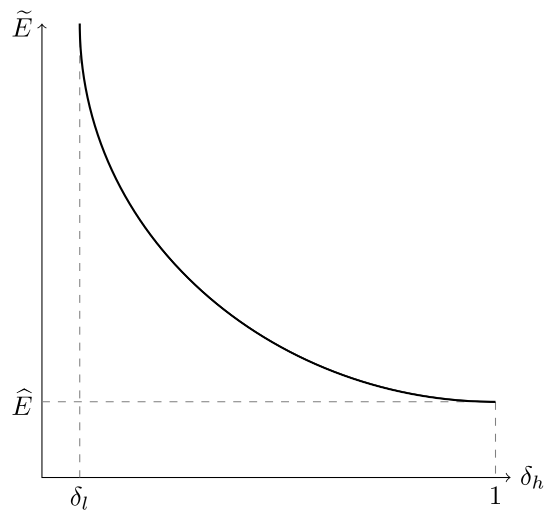

Figure 6: $\widetilde{E}$ as a function of δ_h

We have also shown that, generally, a higher wage premium slows growth. Thus, we can conclude that in this economy moral hazard hampers growth: the bigger the informational problem (intermediate values of δ_h), the lower the growth. Moreover, Figure 6 also shows that the higher the R&D success probability, the lower the expected wage premium, which stimulates growth through a higher hiring of researchers.

Finally, our economy suffers from absolute scale effects. Certainly, population L enhances growth, since more population means more researchers, more designs and higher growth. However, even though the presence of scale effects could undermine the global appeal of the results, our intention is to show the effects of R&D effort, R&D success probabilities and information on growth. Despite its shortcomings, we consider that this paper offers relevant insights on

[15] Although we do not provide a formal proof, numerical simulations for a broad range of parameters confirm this result, which is furthermore consistent with the economic intuition.

these questions.

6 Conclusions

Through the present paper we have discussed the effects on growth of some inherent characteristics of researching. We have shown that augmenting the R&D effort such that the R&D success probability increases, does not guarantee a higher growth rate, whereas the existence of imperfect information, in the form of moral hazard, hampers growth. R&D is an engine of growth but, without the right incentives, there is no extra growth at all. These results are intuitive and coherent with the literature on innovation.

To conclude this paper, we discuss briefly some implications of the additional features of our model, which can potentially give rise to new lines of research or extensions. First, about R&D success probabilities, it is reasonable to think about them as a measure of the efficiency of research. That way, any action aimed at increasing this efficiency will enhance growth. An interesting example of this could be the addition of capital to the R&D technology, as in Sánchez-Losada (2014). It would be the equivalent of economists using computers: going from manually transposing matrices to compute regressions to using a computer program clearly increased the probability of making relevant findings. Another intuitive modification could be making the R&D success probability a function of the state of the technology, total population, population density, or even knowledge concentration. That way we could mimic the historical perceived evolution of research and invention: thinking back to the Industrial Revolution, many groundbreaking discoveries were made by technicians, with more practical than theoretical knowledge (see Mokyr and Voth, 2009). In terms of our model, that is a situation of low E_h, in the sense of education, but also small difference between δ_h and δ_l. On the contrary, the present time appears as one where the requirements, in terms of knowledge, to be a successful researcher are ever increasing. That would be a situation of high E_h and a large difference between δ_h and δ_l. Therefore, these dynamics can be replicated by making δ_h an increasing function of A and δ_l a decreasing function of A. In addition, the feedback between δ_h and A seems to be consistent with the almost-explosive technological growth perceived in the modern era.

Second, about R&D effort, we have already seen the intuition to make it an increasing function of the state of the technology. Furthermore, we have concluded than any measure leading to a decrease in the effort needed to be a highly productive researcher will enhance growth. Following our simile of effort as education, it would be highly interesting to extend our model to include a public education system. The final result is unclear, as the effect of the taxation necessary for this system collides with the effect of the resulting reduction on E_h.

However, and commenting finally about information, a public education system could ameliorate partially the moral hazard problem, as it would allow the government to certify who has made the effort. Also, following the proposition of defining the discovering probabilities as a function of A, we can argue that the advancement of the technology helps growth by reducing the informational problem. If the gap between δ_h and δ_l is progressively widened, the end result of the researcher's activity will be progressively more informative over the applied effort, thus narrowing the gap between $\widehat{E}$ and $\widetilde{E}$. Finally, any of the usual measures described in the literature, such as monitoring, aimed at reducing the problem of information could result in an increase of the growth rate.

To sum up, we tried to dig deeper in the foundations of research and innovation. Technology, with its increasing presence in our daily life, the blooming possibilities for productivity increases derived from it, and the ever expanding variety of products and commodities it generates, is guaranteed to retain its prominent role between the main factors of economic growth. The study of its basic determinants and its effects over the economy as a whole will continue to be a focal point of the economic science for the decades to come.

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