R&D?A Small Contribution to Productivity Growth

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Abstract

In this paper I evaluate the contribution of R&D investments to productivity growth. The basis for the analysis are the free entry condition and the fact that most R&D innovations are embodied. Free entry yields a relationship between the resources devoted to R&D and the growth rate of technology. Since innovators are small, this relationship is not directly affected by the size of the R&D externalities, or the presence of aggregate diminishing returns in R&D after controlling for the growth rate of output and the interest rate. The embodiment of R&D-driven innovations bounds the size of the production externalities. The resulting contribution of R&D to productivity growth in the US is smaller than three to five tenths of one percentage point. This constitutes an upper bound for the case where innovators internalize the consequences of their R&D investments on the cost of conducting future innovations. From a normative perspective, this analysis implies that, if the innovation technology takes the form assumed in the literature, the actual US R&D intensity may be the socially optimal.

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1 Introduction

According to the NSF, "R&D consists on activities carried on by persons trained, either formally or by experience, in the physical sciences such as chemistry and physics, the biological sciences such as medicine, and engineering and computer science. R&D includes these activities if the purpose is to do one or more of the following things:

1. Pursue a planned search for new knowledge [...]. (Basic research)

2. Apply existing knowledge to problems involved in the creation of a new product or process [...]. (Applied research)

3. Apply existing knowledge to problems involved in the improvement of a present product or process. (Development)."

The NSF also presents a list of activities that must be excluded from the definition of R&D. Among these we find social science expenditures, defined as those "devoted to further understanding [of] the behavior of groups of human beings or of individuals as members of groups [in the following areas]: personnel, economics, artificial intelligence and expert systems, consumer, market and opinion, engineering psychology, management and organization, actuarial and demographic...".

There are two elements from this definition that I would like to highlight. First, the final product of the R&D investments are *new* final, intermediate or capital goods and the effect of R&D on productivity is embodied in these new goods in the sense of Solow [1959]. This means that a firm can only benefit from R&D by using the goods that result from the R&D activities.[1] Second, there are other *intentional non-R&D* innovations that lead to improvements in productivity. These non-R&D innovations are disembodied in the sense that, to enjoy the gains in productivity, firms do not need to adopt any new capital or intermediate good. A few examples may illustrate the distinction. The resources Henry Ford devoted to invent the mass production system were not R&D, and neither are McKinsey's reports, the resources devoted to develop better personnel and accounting practices, or any other managerial innovation. [2]

[1] Of course, R&D labs could benefit from the knowledge created in previous R&D efforts. These R&D externalities are addressed below. What I will not consider is the possibility that final output firms benefit from the knowledge created in the labs without using the goods that embody it.

[2] This distinction is substantive because the degree of embodiment affects the specific mechanisms that prevent

In this paper I focus only on embodied innovations and try to answer the following question: What is the contribution of R&D to the growth of advanced economies? Is it the main factor or does it play a minor role?

This question has been answered before by computing the social return to R&D in a simple econometric framework. Typically, the endogenous variable is the Solow residual and the explanatory variables are the firm's or industry's own R&D intensity and the used R&D from other firms or industries. The estimated return to own R&D ranges from .2 to .5, while for the used R&D the estimate ranges from .4 to .8 with a total social return to R&D of about 70 to 100 percent.[3] These numbers are very large. Indeed, since the average share of non-defense R&D in GDP over the postwar period has been 1.6 percent, they imply that the Solow residual is fully accounted by R&D alone.

Before accepting this conclusion, we should keep in mind an important caveat to this econometric approach. Namely, that there are many factors omitted in the typical regression that affect simultaneously TFP growth and the parties incentives to invest in R&D. The most obvious candidates are anything that enhances disembodied productivity, like the managerial and organizational practices, learning by doing,... All these elements have a clear effect on TFP and at the same time induce firms to invest in R&D. Some evidence in favor of the potential importance of this bias comes from the fact that, after including fixed effects in the regression, the effect of R&D on TFP growth almost disappears (Jones and Williams [1998]).

To overcome this omitted variable bias, I depart from the econometric framework. Instead, I use a model with endogenous development of new technologies to assess the importance of R&D for growth. From a methodological point of view, I do not attempt to calibrate directly the social return to R&D to figure out its role on growth. My route is more indirect because it decomposes the problem into two parts. First, I compute the effect of the amount of resources devoted to R&D on the output of the R&D sector (that is the growth rate of R&D driven technologies). Then, I use simple growth accounting to compute the effect of the growth of technology on productivity growth.

One possible way to establish the first relationship (i.e. between the resources devoted to R&D and the growth rate of technology) consists in calibrating the production function of technology. This approach, however, entails probably even more challenges than the traditional productivity

the imitation of the innovation and also the size of the externalities in production.

[3]See Griliches [1992], Jones and Williams [1998] and Nadiri [1992] for references.

approach because in addition to measuring the externalities involved in R&D, we have to specify an R&D production function. I discuss this further below in the context of a specific empirical test.

The approach I propose in this paper, instead, exploits the free entry condition into R&D and the fact that R&D innovations are embodied. Free entry implies that, in equilibrium, R&D firms break even. As a result, the value of the resources devoted to R&D equals the value of the newly developed technologies. In other words, the relationship between the share of resources devoted to R&D and the growth rate of technology is a linear function of the inverse of the market value of an innovation. The advantage of using a free entry condition instead of the production function for innovations is that, since innovators are small, they don't take into account the effect of their investment decisions on the aggregate variables when computing the value of an innovation. Therefore, I can use these observable aggregate variables to establish the effect of the R&D investments on the growth rate of technology without having to take any stand on the production function for new technologies.

The results I obtain are quite striking given the existing consensus about the importance of R&D for growth.[4] The average annual growth rate of productivity in the US during the post-war period has been 2.2 percentage points. Less than 3 to 5 tenths of 1 percentage point are due to R&D.

The intuition for this small contribution is quite simple. The few resources devoted to R&D signal a small private value of the innovations. But, as the bulk of the productivity literature has argued, there may be significant externalities that lead to large productivity gains even with few R&D investments. These externalities can appear in the production of final output or in the R&D process.

Production externalities arise because the development of one innovation has an effect on labor productivity beyond its contribution to the capital stock (i.e. it affects the Solow residual). When innovations are embodied, firms enjoy production externalities to the extent that they use the new goods. Further, a larger production externality implies that, for a given number of available innovations, the demand faced by new innovators is higher. Therefore, *ceteris paribus*, the market value of an innovation is positively correlated with its social value. In terms of my two-step approach, this means that a larger production externality raises the effect of the growth of technology on productivity growth but reduces the growth of technology associated with a given R&D intensity.

[4]The only exception to this consensus is the BLS who reports a R&D contribution to Total Factor Productivity growth of 0.2 percentage points. This difference steams from the rate of return for R&D that the BLS imputes which is substantially lower than in the rest of the literature.

As a result, the R&D contribution to productivity growth is not very sensitive to the size of the externalities in production.

R&D externalities associate past R&D investments with a reduction in the cost of developing future innovations. To show the inconsistency of large R&D externalities and a low R&D intensity in steady state, suppose for a moment that the R&D externalities were large and that the economy is in steady state. Then, a small R&D intensity today, can generate a large growth rate of technology that in turn generates a large reduction in the costs of developing innovations tomorrow. As a result, tomorrow, agents want to devote a large share of resources into R&D; but this is inconsistent with the fact that the share of resources devoted to R&D is constant in steady state. Therefore, the observed low R&D intensity indicates that R&D externalities cannot be very large.

The rest of the paper is structured as follows. Section 2 sketches the basic argument. In section 3, I conduct the baseline calibration based on the model presented in Jones and Williams [2000]. This model is quite general and can accommodate idea-based models both with quality ladders and increasing variety of intermediate inputs. In this section I also discuss the comprehensiveness of the NSF measures of the R&D intensity. One clear goal of this paper is to show that the magnitude of the calibrated R&D contribution to productivity growth is very robust. Section 4 tries to show this by investigating elements that affect the relationship between the share of resources devoted to R&D and the growth rate of technology (for example the presence of increasing returns in the production of R&D driven technologies, international spillovers, ...). I also consider more general production functions that accommodate more flexible relationships between R&D-driven technology and productivity growth. This analysis emphasizes the importance that R&D innovations are embodied. In this sense, this paper contributes to the literature that started with Phelps [1962] on the relevance of the decomposition between embodied and disembodied technological progress. In section 4.3, I move out of the steady state and consider how the calibrations would change had the US economy been in transition to the steady state. In section 5, I draw the welfare implications of the previous analysis. Specifically, the free entry condition establishes a relationship between the R&D intensity and the growth rate of technology that can be used to calibrate the size of the R&D externalities. Once this is done, we can solve the social planner's problem. This entails determining how much she would invest in R&D with the calibrated production structure. Then we can compare this socially optimal R&D intensity with the actual intensity and draw the appropriate policy prescriptions.

The resulting picture after this journey is that R&D plays an small role in US productivity growth - definitely much smaller than what we thought - and that the observed R&D intensity may not be as far from the socially optimal intensity as previous work concluded.

2 The basic argument

Let's denote by A the level of technology associated with R&D investments. In the terminology of Romer [1990] or Grossman and Helpman [1991, ch. 3], this is the number of capital varieties though I will show later that this framework can accommodate other interpretations. To compute the R&D contribution to productivity growth, I start by investigating the relationship between the amount of resources devoted to R&D (expressed in units of final output, which is the numeraire), R, and the growth rate of technology. Then I use a production function to relate the growth rate of A to the growth rate of labor productivity. Throughout the paper I use $\dot{X}$ to designate the time derivative of variable X, and γ_X to denote the growth rate of variable X.

Let P_A denote the market price of a firm that has earned a patent to produce one of these varieties. The free entry condition implies that innovators make zero profits in equilibrium, therefore the cost incurred to develop the patent (R) is equal to the market value of the flow of new technologies ($P_A\dot{A}$).

$$P_A\dot{A} = R. \tag{Free Entry}$$

The free entry condition can be rewritten as in equation (1), where Y denotes the economy-wide output, s denotes the share of resources devoted to R&D (i.e. $s \equiv \frac{R}{Y}$).

$$P_A\ \gamma_A = s\frac{Y}{A} \tag{1}$$

Successful innovators can charge a markup (η) above the marginal cost of production either because they earn a patent or because they keep secret the blueprint of the innovation. As we shall see, the static operating profits earned by an innovator are

$$\pi = \frac{\eta - 1}{\eta}\alpha\frac{Y}{A}. \tag{2}$$

To close the first step in the argument, we just have to derive the market price of an innovation. Suppose for simplicity that patents do not expire and that innovators are not overtaken by new innovators with more sophisticated capital goods. Then the value of an innovation, P_A, must satisfy the following asset equation:

$$rP_A = \pi + \dot{P}_A, \tag{3}$$

where r is the relevant discount factor.

In steady state, all variables grow at constant rates. From equation (1), this implies that

$$\gamma_{P_A} = \gamma_Y - \gamma_A. \tag{4}$$

Substituting expressions (4), (2) and (1) into equation (3) and isolating γ_A we obtain the following expression for the growth rate of technology in terms of s :

$$\gamma_A = \frac{r - \gamma_Y}{\frac{\eta-1}{\eta}\frac{\alpha}{s} - 1} \tag{5}$$

There are two important observations from this expression. First, γ_A in expression (5) does not depend directly on the size of the externalities in R&D or on the degree of the diminishing returns to aggregate R&D investments;[5] note that I have not even specified the production function for technologies. This is the case because we have mimicked the calculations made by small innovators that want to figure out the market price of their innovations (P_A) and do not take into account the effect of their investment decisions on aggregate variables like the interest rate or the growth rate of output. Since the externalities appear through these aggregate variables, we do not need to calibrate them once we control for γ_Y and r. Second, the quantitative result of the paper comes from the fact that γ_A is increasing in s. The link between these two variables does not come from a production function for technology; it follows from the positive relationship that the free entry condition (1) defines between the two.

The second step in the computation of the R&D contribution to productivity growth consists in calibrating the effect of the growth rate of R&D driven technology (γ_A) on the growth rate of productivity. For this we need to specify a production function of the form

$$Y = F(Z, A, K, L)$$

where Z is the level of disembodied productivity and K and L denote capital and labor respectively. From here, the contribution of R&D to productivity is

$$\left[\alpha_A + \alpha\frac{\partial K}{\partial A}\right]\gamma_A,$$

[5]In section 4.1.4 I generalize the analysis to allow for dynamic increasing returns in R&D at the firm level by conceding incumbents a cost advantage in subsequent R&D.

where α is the capital share and α_A is the elasticity of Y with respect to A (i.e. the production externality).

It is useful to assign some tentative values to these parameters to make some back to the envelope calculations about the R&D contribution to productivity growth. A conservative value for η is 1.2, α is about 1/3, r is around 0.07, γ_Y has been 0.034 in the post-war period, s is approximately 0.02 and the elasticity of productivity growth with respect to R&D-driven technology growth $\left(i.e.\ \alpha_A + \alpha \frac{\partial K}{\partial A}\right)$ is about 0.1. This implies that γ_A is about 0.02, and $\left[\alpha_A + \alpha \frac{\partial K}{\partial A}\right] \gamma_A$ is about two tenths of one percentage point.

From this analysis, it is quite transparent that my calibration of the size of the R&D contribution to productivity growth is affected by elements that influence the pricing of an innovation, and the elasticity of output with respect to technology. As we shall see in section 3, the markup η contains information about the set of possible values of α_A and $\frac{\partial K}{\partial A}$. Moreover, once I introduce a variable size of the production externalities in section 4.1 in the context of embodied innovations, I show that there is a trade off between the effect of γ_A on the growth rate of productivity and the effect of s on γ_A. This trade off limits the R&D contribution to productivity growth when production externalities (α_A) are large.

Next, I extend this simple example to illustrate the above claims.

3 Jones and Williams

The baseline model I calibrate is presented in Jones and Williams [2000]. It is a generalization of Romer [1990] and Grossman and Helpman [1991, ch.3]. Final output is produced out of labor and intermediate goods (x_{it}). In particular, I assume the functional form in equation (6). This specification introduces a wedge between the capital share and the elasticity of substitution across different varieties which is equal to $\alpha\rho$.

$$Y_t = Z_t L_t^{1-\alpha} \left(\sum_{i=1}^{A_t} x_{it}^{\alpha\rho} \right)^{\frac{1}{\rho}} \tag{6}$$

Standard profit maximization implies the following inverse demand curve for intermediate goods

$$p_{it} = \alpha L_t^{1-\alpha} \left(\sum_{i=1}^{A_t} x_{it}^{\alpha\rho} \right)^{\frac{1}{\rho}-1} x_{it}^{\alpha\rho-1}.$$

As is commonly assumed in the literature of endogenous technological change, successful developers of intermediate goods are granted infinitely lived patents that allow them to charge a markup (η) over and above the marginal cost of production (r_t).[6] The size of this markup depends on the specific assumptions made about the degree of substitutability between different intermediate goods. Following Jones and Williams [2000], I introduce the concept of innovation clusters to model the idea that there is some overlap between new and existing innovations that causes the obsolescence of the latter. Say, out of every $(\psi_N + \psi)$ intermediate goods developed, only ψ_N are completely new. The rest are just new versions of existing intermediate goods that are necessary to use the new intermediate good. These new versions are otherwise identical to the existing ones.[7] Note that this mechanism is similar to the Schumpeterian process of *creative destruction* emphasized by Aghion and Howitt [1992] and Grossman and Helpman [1991, chapter 4] and therefore limits the expected life span of the innovation.

When a new technological cluster is developed, the incumbents try to prevent the diffusion of the new technological cluster by reducing their prices. Two scenarios are possible here. It may be the case that these reactions do not constrain the pricing decisions of the innovators. Then the innovator charges the monopolist price $p = \eta^m r_t$, where $\eta^m = (\alpha\rho)^{-1}$. Alternatively, the limit pricing rule may be binding. Since in reality we observe that new products are developed and adopted I focus on the equilibrium where new intermediate goods are immediately adopted.[8] After imposing this restriction we can derive the limit pricing rule that is consistent with the adoption of new varieties. Jones and Williams [2000], show that the markup under limit pricing is

$$\eta^L = \left(\frac{\psi_N}{\psi} + 1\right)^{\frac{1}{\alpha\rho} - 1}.$$

Intuitively, the higher the ratio of the number of new goods to the number of complementary goods that must be changed to use the new innovation ($\frac{\psi_N}{\psi}$), the lower is the limit markup because more incumbents are willing to reduce their prices to prevent adoption. Quite naturally, the limit price is also decreasing in the elasticity of substitution across intermediate goods. The resulting price for

[6] The calibrated effect of R&D on growth is independent of the rate of transformation between final output and intermediate goods. This parameter that here is normalized to 1 just cancels out.

[7] A simple example that illustrates this concept is a CD writer. Before the CD writer was developed, we just had a CD reader and a software for this to work. Now with the CD writer, we must modify the CD reader's software to make possible the interaction between the two drives. In this case, $\psi = 1$ (the software) and $\psi_N = 1$ (the CD writer).

[8] If this is not the case, there is no reason to undertake R&D investments.

intermediate goods is $p_{it} = \eta r_t$ where the markup is the minimum of η^m and η^L.

$$\eta = \min \left\{ \overbrace{\frac{1}{\alpha\rho}}^{\text{monopolistic markup}}, \overbrace{\left(1 + \frac{\psi_N}{\psi}\right)^{\frac{1}{\alpha\rho}-1}}^{\text{limit pricing markup}} \right\}$$

Given this pricing behavior, the instantaneous profits of an innovator are:

$$\pi = \left(\frac{\eta - 1}{\eta}\right) \alpha \frac{Y}{A} \tag{7}$$

3.1 R&D technology

The R&D sector uses final output to produce new designs for intermediate goods. The production of designs considered here captures three interesting elements. First, because of the innovation clusters defined above, only a fraction $\frac{\psi_N}{\psi_N+\psi}$ of the designs corresponds to new varieties. Second, either by randomness or because of patent races, there may be a duplication of R&D effort. This *stepping on toes effect* is captured by $\lambda \in (0, 1]$ in equation (8). Finally, there are some spillovers from past innovators to the current ones. On the one hand, new varieties are easier to develop because their designs take advantage of the knowledge created by previous researchers (*standing on the shoulders effect*). On the other, there may be diminishing technological opportunities that make it harder to develop successive varieties (*congestion effect*). If the standing on shoulders effect dominates, $\phi > 0$, otherwise $\phi < 0$. From the point of view of the atomistic researchers, there are constant returns to the resources devoted to R&D (R). This means that they perceive a marginal product equal to the average product over all the R&D firms. This is represented by $\tilde{\delta}$ in equation (8).

$$\frac{(\psi_N + \psi)}{\psi_N} \dot{A} = \tilde{\delta} R \equiv \delta R^\lambda A^\phi \tag{8}$$

Note that this specification accommodates both deterministic and stochastic technologies for the production of new varieties. Indeed, equation (8) is isomorphic to a quality ladder model where $\tilde{\delta}$ is interpreted as the probability of being successful and ψ_N is the size of the step in a quality ladder model á la Aghion and Howitt [1992] and Grossman and Helpman [1991, chapter 4].

Equation (8) can be rewritten as

$$\frac{(\psi_N + \psi)}{\psi_N} \gamma_A A = \tilde{\delta} s Y \equiv \delta \left(sY\right)^\lambda A^\phi. \tag{9}$$

From the R&D technology (9) it follows that the effect of the intensity of R&D investment (s) on γ_A depends on the size of intertemporal spillovers in R&D (ϕ) and on the degree of diminishing returns in the production of varieties (λ). One way to assess the role of R&D in productivity growth consists in calibrating the effect of s on γ_A from (9), and then use the production function (6) to relate γ_A and productivity growth. The main problems with this approach are that it is sensitive to the particular functional form assumed in (9) and that it is difficult to assess the magnitudes of λ and ϕ.[9] Therefore, it is convenient to find an alternative route that avoids the calibration of λ and ϕ. This shortcut comes from the free entry condition.

3.2 Free entry

If innovators are large, they internalize the intertemporal effects of their current R&D investments and the aggregate (static) diminishing returns to R&D. When innovators are small, they take as given the cost of developing a new product and neglect any externality from their investment. In this scenario, free entry brings down the value of innovations to the up front cost of development. Let's denote by P_A the market value of an innovation. Then, the equilibrium level of resources devoted to R&D is given by equation (10).

$$P_A \frac{\psi_N + \psi}{\psi_N} \dot{A} = R \tag{10}$$

Since innovations are priced in the market, P_A must satisfy an asset equation. This means that any difference between the opportunity cost of an innovation and the sum of its profit flow plus the capital gain must be arbitraged away. More formally,

$$\begin{aligned} \overbrace{rP_A}^{\text{opportunity cost}} &= \overbrace{\pi}^{\text{profit flow}} + \overbrace{\dot{P}_A - \frac{\psi}{\psi_N}\gamma_A P_A}^{\text{capital gain}} \\ r &= \frac{\pi}{P_A} + \gamma_{P_A} - \frac{\psi}{\psi_N}\gamma_A \end{aligned} \tag{11}$$

where r is the interest rate faced by innovators, $\dot{P}_A$ is the increase in the market value of the design and $\frac{\psi}{\psi_N}\gamma_A$ is the expected loss from being replaced by another innovator.

Equation (10) can be rewritten as:

$$P_A = \frac{s\psi_N}{\gamma_A(\psi_N + \psi)} \frac{Y}{A} \tag{12}$$

[9] This is precisely one of the main problems with the econometric attempts to compute the social return to R&D.

Using equations (7) and (12) we solve for the profit rate, and from equation (12), we can derive an expression for the growth rate of P_A in steady state.

$$\frac{\pi}{P_A} = \frac{\left(\frac{\eta-1}{\eta}\right)\alpha\left(\psi_N+\psi\right)\gamma_A}{s\ \psi_N}$$

$$\gamma_{P_A} = \gamma_Y - \gamma_A$$

Plugging this back into (11) we can solve for the growth rate of varieties (γ_A).

$$r = \overbrace{\frac{\left(\frac{\eta-1}{\eta}\right)\alpha\left(\psi_N+\psi\right)}{s\ \psi_N}}^{\text{profit rate}}\gamma_A + \overbrace{\gamma_Y - (1+\frac{\psi}{\psi_N})\gamma_A}^{\text{capital gain rate}} \tag{13}$$

$$\gamma_A = \frac{r-\gamma_Y}{\left(\frac{\left(\frac{\eta-1}{\eta}\right)\alpha}{s}-1\right)\left(1+\frac{\psi}{\psi_N}\right)} \tag{14}$$

Now we can easily solve for the growth rate of productivity and use this expression to figure out the contribution of R&D to productivity growth. From the production function,

$$\gamma_{Y/L} \equiv \gamma_Y - \gamma_L = \gamma_Z + \frac{1}{\rho}\gamma_A + \alpha\left(\gamma_x - \gamma_L\right) \tag{15}$$

To solve for γ_x, I take advantage of the symmetry of the intermediate goods in production. From the pricing rule and the inverse demand function, it follows then that

$$x_i = L\left(\alpha Z\frac{A^{\frac{1-\rho}{\rho}}}{\eta r}\right)^{\frac{1}{1-\alpha}}.$$

In steady state r is constant and therefore $\gamma_x - \gamma_L = \frac{1-\rho}{\rho(1-\alpha)}\gamma_A$. Plugging this back into (15), we obtain the following expression for the growth rate of productivity:

$$\gamma_{Y/L} = \frac{1}{1-\alpha}\gamma_Z + \overbrace{\frac{1}{\rho}\left(\frac{1-\alpha\rho}{1-\alpha}\right)\gamma_A}^{\text{Contribution of R\&D to productivity growth}} \tag{16}$$

Before calibrating the R&D contribution to productivity growth it is worthwhile making a few remarks. The specification of the production function for new technologies does not affect the calibration of the role of R&D on productivity growth. In particular, the size of the intertemporal externalities, ϕ, and the returns to scale in the production of varieties, λ, do not affect the relationship between s and γ_A after controlling for r and γ_Y. This is the case because the agents are small and do not internalize the effect of their investment decisions on these aggregate variables. However, expression (13) restricts the values of ϕ and λ. To see this, note that in steady state, equation (9) implies that

$$\gamma_A = \frac{\lambda}{1-\phi}\gamma_Y.$$

Therefore, a low γ_A implies that neither λ nor ϕ cannot be very large. In section 5, I take advantage of this observation to compute the socially optimal R&D intensity and explore whether there is room for a more active R&D policy.

A second remark worth making is that, since the focus of this paper is the contribution of R&D to long run productivity growth, we just need that the free entry condition holds on average for the basic argument to go through.

Finally, note also that, since the baseline model is isomorphic to a quality ladder model, the R&D contribution to productivity growth that I compute next is independent of the actual structure of the R&D process.

3.3 Quantitative Analysis

To assess the role of R&D in productivity growth we must calibrate seven parameters.

Table 1: Parameters

r	0.07
γ_Y	0.034
α	0.33
s	0.02
η	[1.2, 1.5]

s is calibrated using data from the National Science Foundation (NSF). The NSF estimates the expenditures from four surveys (Research and Development in Industry, Academic Research and Development Expenditures, Federal Funds for Research and Development, and Survey of R&D Funding & Performance by Nonprofit Organizations). Funds used for R&D refer to current operating costs. These costs consist on both direct and indirect costs. They include not only salaries, but also fringe benefits, materials, supplies, and overhead. The R&D costs also include the depreciation of the capital stock employed in R&D activities.

To the extent that these surveys encompass only existing institutions, they will be ignoring the current R&D investments conducted by starting firms. For example, the NSF statistics ignore Bill Gates' time spent tinkering in his garage. The omission of these expenditures is probably not very relevant from a quantitative point of view. This claim follows from the fact that in 1999 only 4 percent of total industrial R&D came from firms with less than 25 employees. This number is an upper bound for the average share of R&D from small firms for the post-War period since in 1998 it was only 3 percent and in 1997, the share of industrial R&D from small firms was only 2 percent. Since most start ups become small incorporated firms and continue doing R&D (surely more intensively than before incorporation), these small fractions should give us an idea of the small magnitude of the bias.

Figure 1 plots the evolution of the share of US non-defense R&D expenditures in the US GDP as reported by the NSF. The average over the post-War period is about 1.6 percent. In my calibrations, I use a value for s of 0.02, which is an upper bound for the average share of resources devoted to non-defense R&D during the post-war period in the US.[10]

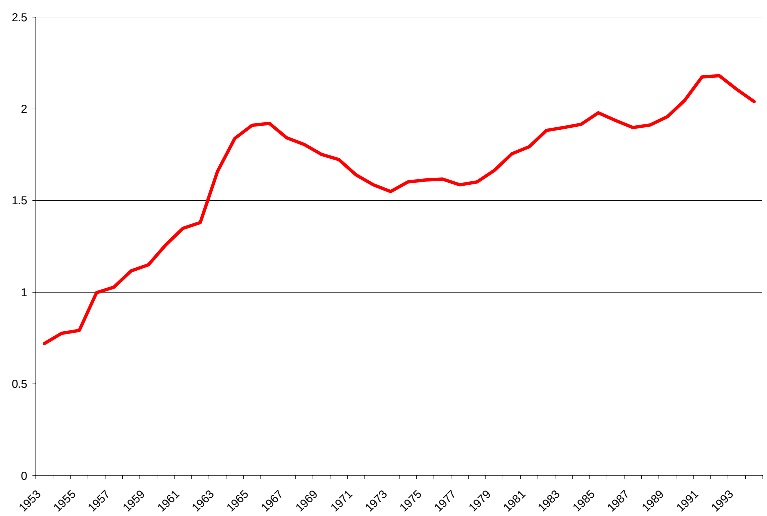

Figure 1: US share of non-defense R&D expenditures in GDP in percentage points. Source: NSF.

r is calibrated to the average real stock return in the US post-war period from Mehra and Prescott [1985]. Pakes and Schankerman [1984] provide evidence that this is approximately the private rate

[10]Later in this section, I conduct a sensitivity analysis to show that the small R&D contribution to productivity growth is robust to large mismeasurement by the NSF of the R&D intensity. In any case, the productivity literature has used this same data to claim that there is a large contribution of R&D to productivity growth.

of return to R&D once we take into account the obsolescence of patents and the gestation lags that I incorporate in the next section. The average real growth rate of output (γ_Y) between 1950 and 1999 in the US reported by the BLS is 0.034. The capital share (α) is calibrated to $\frac{1}{3}$. The markup (η) is calibrated with values in the interval [1.2, 1.5] that lies in the intervals given by Basu [1996] and Norrbin [1993] for the average markup in the economy. The lower values of this interval are slightly higher than the lower bound in Basu [1996] and Norrbin [1993] because I want to calibrate the markup charged by an innovator. This is probably higher than the average markup in the economy because of the monopolistic power conferred by the patent system and because the higher ratio of the up front fix cost to the marginal cost of production for technological goods than for non-technological goods or services.[11]

I do not attempt to calibrate $\frac{\psi}{\psi_N}$.[12] To calibrate ρ, I exploit the relationship between these variables and the markup. There are two cases depending on whether the innovator can charge the monopolistic markup or whether she is forced to use the limit pricing rule.

Case 1: If $\eta = \frac{1}{\alpha\rho}$ then $\frac{1}{\rho} = \eta\alpha$. Figure 2 plots the contribution of R&D to productivity growth for different values of η and $\frac{\psi}{\psi_N}$. In the post-WWII period, the US productivity has grown at an average annual rate of 0.022. In the figure we can see that under monopolistic pricing the contribution of R&D to growth is bounded above by two tenths of one percentage point. That is, R&D cannot account for more than one tenth of the postwar productivity growth under monopolistic pricing of the innovations.

[11] As we shall see below, results hold a fortiori if η is calibrated to a higher (probably more realistic) value.

[12] This could be done by using data on the average life span of a patent or, when more sophisticated concepts of firms are introduced, on the average life span of a firm or on the average number of patents held by an innovator.

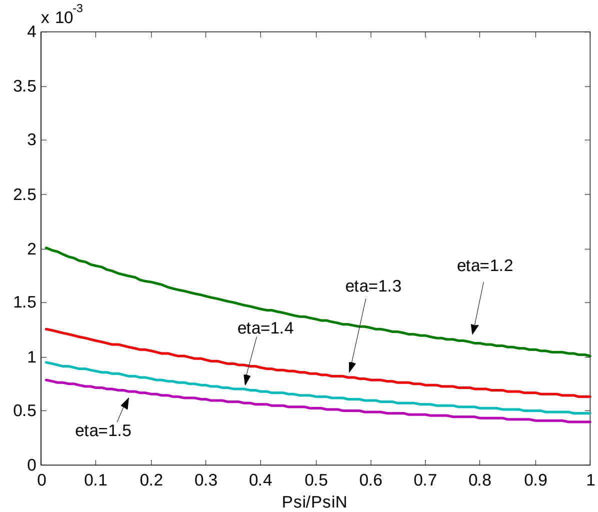

Figure 2: Contribution of R&D to productivity growth, monopolistic pricing.

Case 2: If $\eta = \left(1 + \frac{\psi_N}{\psi}\right)^{\frac{1}{\rho\alpha} - 1}$ then

$$\rho = \left[\alpha\left(1 + \frac{\ln(\eta)}{\ln\left(1 + \frac{\psi_N}{\psi}\right)}\right)\right]^{-1} \tag{17}$$

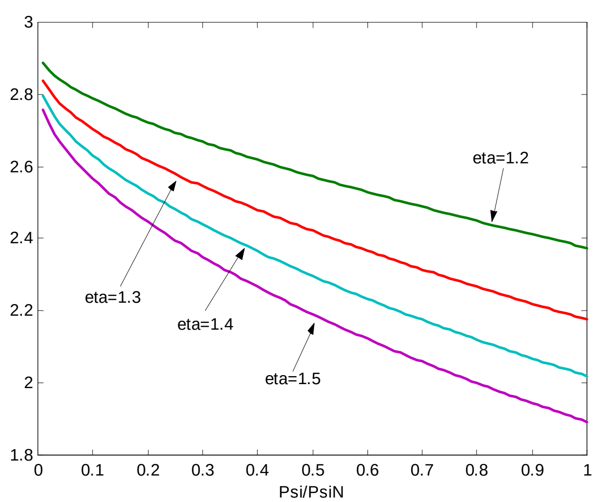

Figure 3: $\rho(\psi/\psi_N|\eta)$

Figure 3 plots the relationship between ρ and ψ/ψ_N implied by the limit pricing rule for several values of η. Figure 4 plots the contribution of R&D to productivity growth as a function of ψ/ψ_N under limit pricing for different markups. In this case, the upper bound of the contribution of R&D to productivity growth is one tenth of a percentage point.

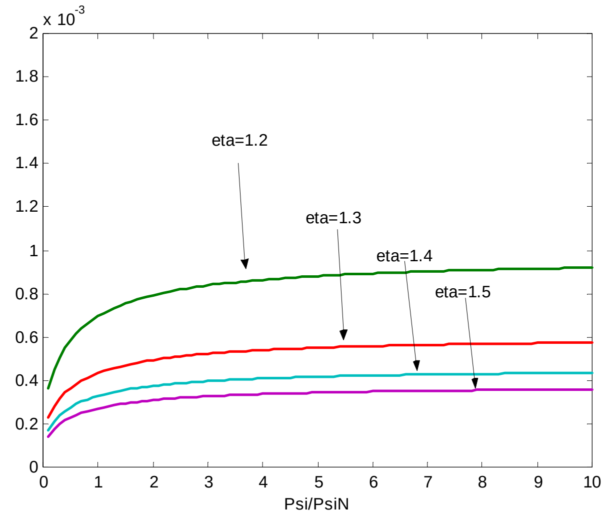

Figure 4: R&D contribution to productivity growth under limit pricing.

These small contributions are the result of three effects. First, the low R&D intensity observed in steady state implies that the externalities in the R&D process are small. Otherwise, future R&D investments would be very profitable and we should observe a large R&D intensity. Second, as we have shown in section 2, the small R&D intensity also implies that the growth rate of A for any given markup must be low. Finally, in this environment where R&D innovations affect productivity through the goods that embody them, the contribution of production externalities to productivity growth is equal to $(\frac{1}{\rho} - \alpha)\gamma_A$. For given α and γ_A, a lower the elasticity of substitution across the different intermediate goods increases the size of the production externalities. However, both under monopolistic and limit pricing, a reduction in the elasticity of substitution also raises the markup (η). Naturally, this results in a higher P_A and, from the free entry condition, in a lower γ_A for any given R&D intensity (s). In other words, the embodiment assumption introduces a trade off between the growth rate of R&D-driven technology and the size of the production externalities that bounds the R&D contribution to productivity.

An interesting observation that arises at this point, is that the effect of ψ/ψ_N on the R&D contribution to productivity growth depends on the pricing rule. Under monopolistic pricing, the

R&D contribution to productivity is decreasing in the ratio $\frac{\psi}{\psi_N}$ because the value of an innovation (P_A) increases with the ratio[13] and, from free entry, this reduces the growth rate of A consistent with the observed R&D intensity. When innovations' prices are limited by the prices of the previous innovations, the contribution is increasing in ψ/ψ_N because, in addition to the previous effect, now ρ decreases in ψ/ψ_N, for any given markup, as illustrated in figure 3. As we have just argued, the size of the production externalities decreases with the elasticity of substitution across varieties, and therefore it increases in the ratio ψ/ψ_N. This effect dominates the effect on P_A and, as a result, the R&D contribution to productivity increases with ψ/ψ_N.

Before enriching the basic model to incorporate other important aspects of the R&D process and more general production functions, it is interesting to assess the robustness of the computed R&D contribution to productivity to the calibration of the interest rate (r) and the R&D intensity (s) .

In other calibrations not reported here, I have observed that the small R&D contribution to productivity growth is very robust to the parameterization of the interest rate (r). This allows me to extend the results to environments where innovators are credit constrained and therefore the opportunity cost of R&D investments is higher.

Figure 5 and 6 display the R&D contribution to productivity growth when s is calibrated in the interval [0.015, 0.03] for six different pairs of $(\eta, \psi/\psi_N)$ that basically cover all the relevant range for these parameters. We can see that both under monopolistic (figure 5) and limit pricing (figure 6), the R&D contribution is still quite small (i.e. bounded above by 0.0035).

[13]This follows because an innovator that has succeeded in developing a new technological cluster collects revenues from $\psi + \psi_N$ goods. At the same time, the probability that future researchers erode his rents in any of these goods is increasing in $\frac{\psi}{\psi_N}$. As in Schumpeterian growth models, the first effect dominates because it comes first in time and, as a result, P_A increases with $\frac{\psi}{\psi_N}$.

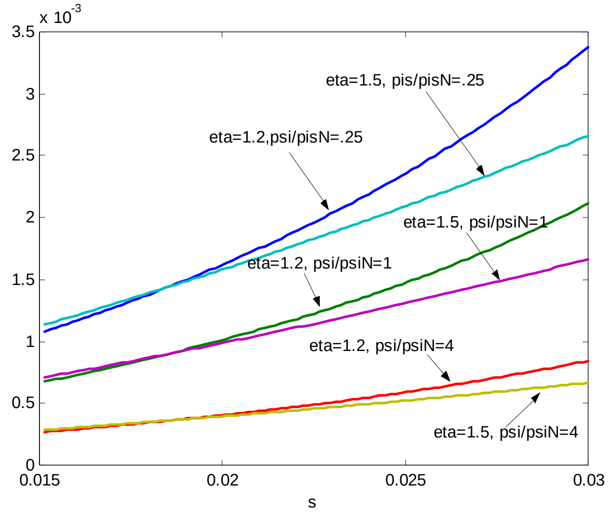

Figure 5: R&D contribution under monopolistic pricing as a function of s, for various η and ψ/ψ_N.

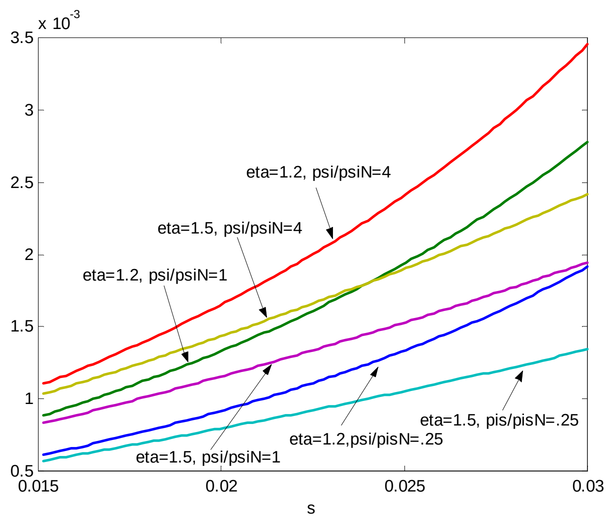

Figure 6: R&D contribution under limit pricing as a function of s for several η and ψ/ψ_N.

4 Extensions

Now, I extend the baseline model along several dimensions to show that the size of the R&D contribution to productivity growth is robust. The first extension generalizes the production function to capture more general externalities in the production of final output. The second group of extensions deals with considerations that affect the private value of an innovation. These include the presence of international spillovers in R&D investments, R&D lags, more drastic obsolescence processes and the possibility of successive R&D for incumbent firms (i.e. firm-level increasing returns to R&D). Then, I relax the assumption that the economy is in steady state and compute the R&D contribution to productivity growth if the US economy had been in transition during the post-war period.

4.1 More general production functions[14]

In the baseline model, the elasticity of productivity growth with respect to γ_A is equal to $\frac{1-\alpha\rho}{\rho} + \frac{\alpha(1-\alpha\rho)}{\rho(1-\alpha)}$, where the first term corresponds to the static externality of A on output and the second to the capital deepening driven by the development of new technologies. One might argue that with a more general production function we could parameterize the externality in production in such a way that R&D generates an arbitrarily large growth rate of productivity.[15]

In what follows, I show that if R&D technologies are embodied this is not the case. Intuitively, the variable production externality introduces a wedge between the *effective* level of R&D-driven technology and A. The embodied nature of R&D innovations implies that to benefit from them, firms must purchase the goods that embody the innovations. If the elasticity of the effective level of R&D technology with respect to A is larger than one, the efficiency of an innovation grows with its vintage. Moreover, a larger the production externality generates a higher effective level of technology embodied in a new good, for a given A, and this, in turn, induces a larger demand and a higher value for the innovations. Hence, when R&D innovations are embodied, the free entry

[14] In this analysis I have assumed that the production function of final output is Cobb-Douglas. Basu [1997], Burnside, Eichembaum and Rebelo [1995] and Berndt [1976] among others have shown that a Cobb-Douglas is a good approximation to the US data. Further, in the working paper version of this article (Comin[2002]) I show that the growth rate of R&D innovations is not very sensitive to the elasticity of substitution between capital and labor.

[15] One such production function would be

$$Y = A^{\sigma} Z \left[\int_0^A x_i^{\alpha\rho} \right]^{\frac{1}{\rho}}.$$

Note that, in this production function, by increasing σ we can increase the size of the production externality and the R&D contribution to growth. However, note also that in this production function R&D innovations are not embodied. Firms do not need to buy a single unit of the lattest innovation to benefit from the productivity gains associated with this innovation. Both, casual observation and the NSF definition of R&D suggest that this assumption does not seem to capture how R&D innovations enter in production.

condition implies that a higher production externality reduces the growth rate of A associated with a given R&D intensity. This effect introduces a trade off that limits how much productivity growth can be explained by increasing the size of the production externalities.

To see this more formally, consider an environment that is exactly the same as in the baseline model but with the following aggregate production function:

$$Y = ZL^{1-\alpha}\left[\int_0^A a_i x_i^{\alpha\rho} di\right]^{\frac{1}{\rho}},$$

where now the level of R&D-driven technology is a continuous variable and the capital varieties have different efficiencies a_i. To introduce some flexibility on the size of the production externality, I set $a_i = bi^{\sigma-1}$, where b is any positive constant that, without loss of generality, I normalize to 1, $\sigma > \alpha\rho$ and i is a technology index. The size of the externality in production is increasing in σ. When $\sigma > 1$, newer innovations are more efficient than older innovations.

The inverse demand for a particular variety i, is

$$p_i = Z\alpha L^{1-\alpha}\left(\int_0^A a_i x_i^{\alpha\rho} di\right)^{\frac{1}{\rho}-1} a_i x_i^{\alpha\rho-1}.$$

Due to the isoelastic nature of the demand, innovators set a price equal to a constant markup η times the marginal cost of production r. Following the same algebraic steps as in the standard model, we can easily find that when the state of the art technology has index A, the level of output is given by expression (18) and the profits for an innovator that developed a variety with index $i \leq A$ are given by (19).[16]

$$Y = LZ^{\frac{1}{1-\alpha}}\alpha^{\frac{\alpha}{1-\alpha}}(\eta r)^{\frac{-\alpha}{1-\alpha}} A^{\frac{\sigma-\alpha\rho}{\rho(1-\alpha)}} \quad (18)$$

$$\pi_{iA} = \frac{\eta-1}{\eta}\alpha \underbrace{\frac{\sigma-\alpha\rho}{1-\alpha\rho}}_{\text{Level effect}} \frac{Y}{A} \underbrace{\left(\frac{i}{A}\right)^{\frac{\sigma-1}{1-\alpha\rho}}}_{\text{Gradual substitution}} \quad (19)$$

[16]It can also be shown that

$$K = \int_0^A a_i x_i di = \chi_K Z^{\frac{1}{1-\alpha}} LA^{\frac{(\sigma-\alpha\rho)(1-\rho)+\rho(1-\alpha)(2\sigma-1-\sigma\alpha\rho)}{\rho(1-\alpha)(1-\alpha\rho)}},$$

where χ_K is a positive constant; and that

$$Y = \chi_Y Z A^{\tilde{\sigma}} K^{\alpha} L^{1-\alpha},$$

where χ_Y is another positive constant and $\tilde{\sigma} = \frac{\sigma(1-\alpha\rho)}{\rho}$.

In this last expression, we can distinguish two effects of σ on the profits of an innovator. The higher curvature in the efficiency of capital vintages (σ), the higher the initial level of profits, but also the faster final good producers gradually substitute towards the new, more efficient, varieties.

Expression (19) can be rewritten in terms of the vintage of the variety sold by the innovator. More specifically, let v_i be the vintage of the i^{th} variety. In steady state, A grows at the constant rate γ_A. Let's suppose that the economy started on the balanced growth path. Then the profits at time t of an innovator that developed a vintage v_i variety are:

$$\pi_{v_it} = \frac{\eta - 1}{\eta}\alpha\frac{Y}{A}\frac{\sigma - \alpha\rho}{1 - \alpha\rho}e^{-\left(\frac{\sigma-1}{1-\alpha\rho}\right)(t-v_i)\gamma_A}. \tag{20}$$

When $\sigma > 1$, the innovations embodied in newer varieties are more profitable than those embodied in older vintages. The converse is true when $\sigma < 1$. Consequently, the market value of an innovation generically varies in the cross-section. Let $P_{At,v}$ denote the price at time t of a vintage v innovation. From free entry, we know that

$$P_{Att} = \frac{s\psi_N}{\gamma_A\left(\psi_N + \psi\right)}\frac{Y}{A}. \tag{21}$$

Since P_{Atv} is determined in the market, it satisfies the following differential equation:

$$rP_{Atv} = \pi_{vt} + \dot{P}_{Atv} - \frac{\psi}{\psi_N}\gamma_A \tag{22}$$

It is easy to see that $P_{Atv} = P_{Att}\ e^{-\gamma_A\left(\frac{\sigma-1}{1-\alpha\rho}\right)(t-v)}$.[17] This implies that $\gamma_{P_{Atv}} = \gamma_Y - \gamma_A\left(\frac{\sigma-\alpha\rho}{1-\alpha\rho}\right)$. Dividing both sides of equation (22) by P_{Avt} and plugging (20) and this expression for $\gamma_{P_{Atv}}$, we can derive expression (23).

$$\gamma_A = \frac{r - \gamma_Y}{\left(\frac{\left(\frac{\eta-1}{\eta}\right)\alpha}{s}\left(1 + \frac{\psi}{\psi_N}\right) - 1\right)\left(\frac{\sigma-\alpha\rho}{1-\alpha\rho}\right) - \frac{\psi}{\psi_N}} \tag{23}$$

This expression differs from the growth rate of technology in the baseline model (13) in two respects. First, the profit rate of innovations increases with σ. Second, a higher σ implies a higher expected capital loss due to the depreciation of the market value of the innovations. The first effect raises the current value of an innovation while the second reduces it. However, in expression (23) it is clear that the first force dominates the second, and the higher is the externality in production (σ) the lower is the growth rate of technology associated with a given R&D intensity.

[17] For this you can solve the differential equation (22) plugging in (20) and using the initial condition (21).

To complete the calculation we just have to derive the growth rate of productivity from expression (18).

$$\gamma_{Y/L} = \frac{1}{1-\alpha}\gamma_Z + \frac{\sigma - \alpha\rho}{\rho(1-\alpha)}\gamma_A$$

Note that, for a given γ_A, the R&D contribution to productivity growth is increasing in σ. However, doing some simple algebra we can check that, after taking into account the effect of σ on γ_A, the R&D contribution to productivity growth is decreasing in σ. To assess the quantitative importance of these effects, I plot the R&D contribution for several values of σ and ψ/ψ_N when the markup is equal to 1.2, in figure 9.[18] For brevity, I restrict myself to the case of monopolistic markups (i.e. $\eta = (\alpha\rho)^{-1}$).

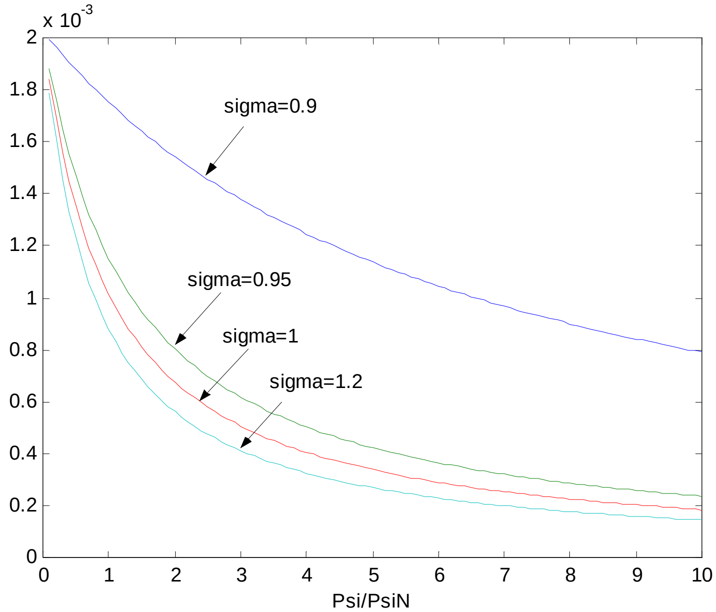

Figure 9: R&D contribution to productivity growth with $\eta = 1.2$ for several $\sigma's$

From this figure, we can see that, if R&D innovations are embodied, the R&D contribution to productivity growth is quite robust to the size of the production externality and it is smaller than two tenths of one percentage point.

This result relates this paper to a literature that has studied the relevance of the distinction between embodied and disembodied productivity growth. The interest in this question started with Phelps [1962] who showed that the elasticity of the steady state level of output with respect to

[18] For higher values of the markups the contribution is smaller.

the savings rate does not depend on the composition of technological progress.[19] On the empirical front, Denison [1964] argued that embodied technological change represents a small fraction of productivity growth. Twenty years later, Mc Hugh and Lane [1987] came out with better estimates that controlled for the cyclical variation in the utilization of capital of different vintages and showed that the contribution of the embodied component of productivity growth was substantial. The argument presented in this section has brought the embodiment hypothesis to the core of the analysis. In line with the replies to Phelps [1962], it has show that the fact that R&D innovations are embodied in new goods is very relevant to calibrate the contribution to labor productivity of R&D investments.

4.2 The value of innovations

In the free entry condition, equation (12), we can see that the relationship between the share of resources devoted to R&D and the growth rate of technology is mediated by the value of innovations. Therefore, in principle, the R&D contribution to growth could be increased by enriching the model with new dimensions of the R&D process that affect the value of innovations. Next, I show that the small contribution is robust to many variations.

4.2.1 International technology flows

Intermediate goods flow internationally. The new technologies developed in Japan can be purchased in the US and used in the production of final output. This observation has two implications for the baseline analysis. On the one hand, I should use the R&D investments conducted in the whole world, and not just in the US, to calibrate the R&D intensity. On the other, a US innovator now can sell her innovation to the whole world, and therefore I should take into account the effect of this larger market size on the value of innovations. In terms of our calibration, the first effect implies that now the free entry condition is

$$P_{A_w} \frac{(\psi + \psi_N)}{\psi_N} \dot{A} = R_w, \tag{24}$$

[19] For the debate that followed see also Matthews [1964], Phelps and Yaari [1964], Levhari and Sheshinski [1967] and Fisher, Levhari and Sheshinski [1969].

where R_w represents the R&D in the world. Following the same logic as above, P_{A_w} can be expressed as:

$$P_{A_w} = \frac{\psi_N s_w}{(\psi + \psi_N)\gamma_A} \frac{Y_w}{A}, \tag{25}$$

where Y_w and s_w denote respectively the world level of output and the share of R&D in the world's output.

The second effect implies that the profits of a successful innovator are a function of the output of the countries where she can sell her innovations. Since innovations can be sold internationally, the new profit flow from a new variety is:

$$\pi_w = \left(\frac{\eta - 1}{\eta}\right) \alpha \frac{Y_w}{A}$$

As before, the value of an innovation is determined in the market and must satisfy an asset equation.

$$r = \frac{\pi_w}{P_{A_w}} + \gamma_{P_{A_w}} - \frac{\psi}{\psi_N}\gamma_A$$

The last term on the right hand side is the same as in the closed economy case. In steady state, equation (25) implies that $\gamma_{P_{Aw}}$ is equal to $\gamma_{Y_w} - \gamma_A$. But the interesting action takes place in the profit rate. There we can see that the two consequences from the internationalization of the economy exactly cancel out. More specifically,

$$\frac{\pi_w}{P_{A_w}} = \frac{\left(\frac{\eta-1}{\eta}\right) \alpha \left(\psi_N + \psi\right)}{s_w \ \psi_N} \gamma_A$$

Intuitively, the international flow of intermediate goods raises the resources devoted to develop the varieties that are ultimately used in the production of US output. The flip side of the coin is that US' (and any other country's) innovators can sell their goods to a larger market. Since both forces are proportional to Y_w, they cancel out.[20]

Plugging this expression into the asset equation (11), we obtain the following growth rate of innovations:

$$\gamma_A = \frac{r - \gamma_{Yw}}{\left(\frac{\left(\frac{\eta-1}{\eta}\right)\alpha}{s_w} - 1\right)\left(1 + \frac{\psi}{\psi_N}\right)} \tag{26}$$

[20] This is not the case if international partners engage in R&D but the US innovators cannot export their products. This scenario, however, seems empirically irrelevant.

This exercise yields some interesting observations. Note that I have not specified any production function for R&D goods. As we have seen above, that is not necessary to calibrate the R&D contribution to productivity growth. In particular, the following general form is perfectly consistent with expression (26):

$$\frac{(\psi+\psi_N)}{\psi}\dot{A}_c = f_c\left(R_c, \{R_{-c}\}, A_c, \{A_{-c}\}\right),$$

where c indexes country c, $-c$ the sequence of other countries different from c and the only restriction on (the possibly country specific) function f_c is that there are diminishing returns in R_c. Note that this function captures all sorts of international spillovers in R&D.

Coming back to the calibration of the R&D contribution to productivity in the presence of international spillovers, it is easy to see that the figures obtained cannot be larger than the ones obtained in the previous section. Note from expression (26) that γ_A is increasing in s_w and decreasing in γ_{Y_w}. In the post-war period, the growth rate of output in the OECD has been higher than in the US, and the share of R&D in GDP is higher in the US than in the OECD. Therefore I keep the previous section's results as upper bounds for the R&D contribution to productivity growth.

4.2.2 Subsequent R&D cost advantage

Up to now, a firm has been characterized by the set of varieties that form an innovation cluster. All of these intermediate goods are developed simultaneously and once they become obsolete the firm vanishes. However, the evidence tells us that a large fraction of innovations are developed by firms that have already developed some other innovation clusters. This can be due to the fact that the costs of innovation decline with the number of varieties developed (i.e. there is some form of increasing returns to R&D at the firm level). If this is the case, innovations are more valuable than what we have computed so far. Investing in R&D not only grants the right to the future revenues from the new innovation cluster but also the option to develop more clusters in the future at a lower cost. To reconcile the higher value of innovations with the observed low s, the free entry condition now dictates a lower growth rate of varieties and a smaller contribution of R&D to productivity growth.

This additional complexity is useful to generalize the argument made above to large firms. These internalize part of the positive consequences of their investment decisions. By taking advantage of part of the externalities, the value of the R&D firm increases, and the growth rate of varieties induced by a given share of R&D is lower than when firms are small. Hence, the benchmark contribution computed above gives an upper bound for the role of R&D in productivity growth when firms are allowed to grow.

To show this more formally, let's suppose that an incumbent firm j with $i > 0$ active innovation clusters has the ability to develop up to i new innovation clusters every instant. Let r_{ij} denote the amount of R&D this firm conducts for each of the i projects. Success at each of the projects arrives with an independent Poisson rate $\delta(r_{ij}, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty})$, where R_i and A_i denote respectively the total R&D investments and the total number of varieties available in the market from the firms with exactly $i-1$ active clusters. The only restrictions I impose on δ are that it is increasing and concave in r_{ij}. Let N_{i-1} be the number of firms with exactly $i-1$ active technological clusters. The framework described so far implies that the total number of clusters developed every instant by firms with already $i - 1 \geq 0$ active technological clusters is

$$\frac{\dot{A}_i}{\psi_N} = N_{i-1}\, i\delta(r_{ij}, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty}). \tag{27}$$

One important modification introduced with this setup is that the firm now internalizes part of the intertemporal consequences of its R&D investments because it is aware that succeeding in developing the next technological cluster increases the chances of developing new clusters in the future. However, for simplicity, I still assume that the number of firms in each size group (N_i) is large and therefore that the effects of r_{ij} on R_i, and of A_{ij} on A_i are negligible.[21] This means that incumbents select r_{ij} to maximize $i\left[\delta(r_{ij}, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty})(V_{i+1} - V_i) - r_{ij}\right]$ taking as given $\{R_c\}_{c=1}^{\infty}$ and $\{A_c\}_{c=1}^{\infty}$.

The optimal level of r_{ij} (denoted by r^*) does not depend directly on i, and satisfies the following first order condition:

$$\frac{\partial\delta(r^*, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty})}{\partial r_{ij}}(V_{i+1} - V_i) = 1, \text{ for } i > 0 \tag{28}$$

From this framework, it follows that

$$\frac{1}{R_i}\frac{\dot{A}_i}{\psi_N} = \frac{\delta(r^*, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty})}{r^*} > \frac{\partial\delta(r^*, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty})}{\partial r_{ij}} = \frac{1}{V_{i+1} - V_i}, \text{ for } i > 0$$

[21] This seems to me the most reasonable scenario: one where firms internalize the cost advantage of subsequent innovation but do not internalize the aggregate diminishing returns to R&D or the aggregate intertemporal externalities.

where the first equality comes from the production function for R&D (27), the inequality is a consequence of the concavity of δ on r_{ij}, and the second equality follows from the first order condition (28). Rewriting this, we observe that incumbent R&D firms make positive profits on average from successive innovations.

$$(V_{i+1} - V_i)\frac{\dot{A}_i}{\psi_N} > R_i \tag{29}$$

For new R&D firms, however, free entry brings down the expected value of a firm with exactly one cluster to the cost of developing the first innovation cluster.

$$V_1\frac{\dot{A}_1}{\psi_N} = R_1 \tag{30}$$

As before, we can derive the relationship between s and γ_A by pricing the R&D firms. The value of a firm with exactly $i \geq 1$ active clusters satisfies the following asset equation:

$$rV_i = i\pi(\psi + \psi_N) + \dot{V}_i - i\frac{\dot{A}}{\psi_N}\frac{(\psi + \psi_N)}{A}(V_i - V_{i-1}) + i\max_{r_i}\delta(r_i, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty})(V_{i+1} - V_i) - r_i$$

Using the definition of r^* and dividing by V_i, we obtain:

$$r = i\frac{\pi}{V_i}(\psi + \psi_N) + \frac{\dot{V}_i}{V_i} - i\frac{\dot{A}}{\psi_N}\frac{(\psi + \psi_N)}{A}\left(\frac{V_i - V_{i-1}}{V_i}\right) + i\delta(r^*, \{R_c\}_{c=1}^{\infty}, \{A_c\}_{c=1}^{\infty})\left(\frac{V_{i+1} - V_i}{V_i}\right) - i\frac{r^*}{V_i}$$

At this point, we can make a very useful observation. If $V_i = iV_1$, the RHS of this equation is independent of i. This means that we can find a solution to this system of difference equations by just solving the one for V_1. Using this shortcut we can reduce the system to:

$$r = \frac{\pi}{V_1}(\psi + \psi_N) + \frac{\dot{V}_1}{V_1} - \frac{\dot{A}}{\psi_N}\frac{(\psi + \psi_N)}{A} + \overbrace{\delta(r^*, \{R_i\}_{i=1}^{\infty}, \{A_i\}_{i=1}^{\infty}) - \frac{r^*}{V_1}}^{\text{profit rate from subsequent R\&D}} \tag{31}$$

The free entry condition for new innovators (30) implies that:

$$V_1 = \frac{s_1\psi_N}{\frac{\dot{A}_1}{A_1}\frac{A_1}{A}}\frac{Y}{A},$$

where s_1 is the share of R&D conducted by entrants in total output. Since in the steady state γ_{A_1}, s_1 and $\frac{A_1}{A}$ are constant, $\gamma_{V_1} = \gamma_Y - \gamma_A$.

From (30) and (29) it follows that

$$\begin{aligned}
\sum_{i=1}^{\infty}(V_i - V_{i-1})\frac{\dot{A}_i}{\psi_N} &> \sum_{i=1}^{\infty} R_i \\
V_1 \frac{\dot{A}}{\psi_N} &> R \\
V_1 &> \frac{s\psi_N}{\gamma_A}\frac{Y}{A}, \qquad (32)
\end{aligned}$$

where the second inequality takes advantage of the fact that $V_i = iV_1$.

Plugging (32) into the asset equation (31) we obtain the following inequality:

$$r > \frac{\left(\frac{\eta-1}{\eta}\right)\alpha(\psi+\psi_N)}{s\psi_N}\gamma_A + \gamma_Y - \gamma_A - \frac{(\psi+\psi_N)}{\psi_N}\gamma_A + \overbrace{\delta(r^*, \{R_i\}_{i=1}^{\infty}, \{A_i\}_{i=1}^{\infty}) - \frac{r^*}{V_1}}^{>0}$$

And from here,

$$\gamma_A < \frac{r - \gamma_Y - \overbrace{\left(\delta(r^*, \{R_i\}_{i=1}^{\infty}, \{A_i\}_{i=1}^{\infty}) - \frac{r^*}{V_1}\right)}^{>0}}{\frac{\left(\frac{\eta-1}{\eta}\right)\alpha e^{-(r-g_Y)l}}{s}\left(1+\frac{\psi}{\psi_N}\right) - \left(2+\frac{\psi}{\psi_N}\right)}$$

To relate this expression with the growth rate of varieties when innovators are small (13), recall that incumbents make positive profits from subsequent R&D. This means that the new term in the numerator is strictly positive and that instead of an equality, now we have an strict inequality. As a result, the γ_A implied by s when we allow firms to partially internalize the future cost advantages of their current R&D (i.e. when they are large) is lower than when they are small.

4.2.3 Further extensions

R&D lags In reality there is a lag between the outlay of the R&D investment and the beginning of the associated revenue stream. This lag corresponds both to the lag between project inception and conception (the gestation lag), and the time from project completion to commercial application (the application lag). Rapoport [1971] and Wagner [1968] have gathered data on lags for 52 technologies in various manufacturing sectors and have found that these lags range between 1.5 and 2.5 years. In Comin [2002] I show that introducing these lags in the analysis has a very small effect on the previous calculations.

Correlated shocks In the baseline model we have assumed that the obsolescence shocks are independent across the different intermediate goods in a common innovation cluster. This is probably not a very realistic assumption. When a new technological cluster is developed, there is a chance that it drives out of the market a large number of intermediate goods of an older cluster. In this scenario, the shocks faced by the intermediate goods in a given cluster are highly correlated. In Comin [2002] I model this idea in the simple case where each new technological cluster makes completely obsolete an older cluster. This is precisely the structure of the simple quality ladder models. It turns out from my analysis that even after introducing correlated shocks and R&D lags, the contribution of R&D to productivity growth for the more reasonable markups is bounded above by 3 to 5 tenths of one percentage point.

Imitation Another relevant extension consists in relaxing the assumption of perfect enforcement of patents. If imitators can copy the goods developed by the innovators, the value of innovations declines and the free entry condition yields a higher growth rate of A for any given R&D intensity. Nevertheless, imitation does not affect substantially the R&D contributions to productivity growth computed above. Mansfield el al. [1981] have information about the probability that an innovation is imitated and about the average cost of imitation. If in addition we recognize that imitations are not more valuable than the original innovations, then we can easily redo our calculations and observe that the R&D contribution to productivity growth is bounded above by 3 to 5 tenths of one percentage points.[22] .

4.3 Transition and relation to Jones [2001]

Jones [2001] has argued that the US economy has been in a transition to the steady state during the post-war period. In this section I extend the previous analysis to the transition and relate my findings to Jones [2001].

When deriving the relationship between s and γ_A, I have assumed that the economy is in steady state only to compute the price appreciation of the innovations. Remember that free entry implies

[22] Probably, this upper bound overstates the contribution of R&D because some of the imitation expenses are likely to be reported as research and development expenses in the NSF surveys. This would have the effect of reducing s in our calculations, and from the free entry condition, would result in a lower γ_A and in a lower contribution to productivity growth.

that

$$P_A = \frac{s\psi_N}{\gamma_A(\psi_N + \psi)} \frac{Y}{A}.$$

If the economy is in the transition, then

$$\gamma_{P_A} = \overbrace{\gamma_Y - \gamma_A}^{\text{Steady State}} + \overbrace{\gamma_s - \gamma_{\gamma_A}}^{\text{Transition}}.$$

The asset pricing equation holds at every instant, but now we have to recognize the new expression for the price appreciation of an innovation. This yields the following differential equation for γ_A:

$$\frac{d(\ln(\gamma_A))}{dt} - \left[\frac{\eta - 1}{\eta}\frac{\alpha(\psi_N + \psi)}{s\psi_N} - \left(1 + \frac{\psi}{\psi_N}\right)\right]\gamma_A = -(r - \gamma_Y - \gamma_s) \tag{33}$$

Since s is time varying this differential equation does not have a closed form solution. To approximate the average growth rate of A, we can solve this differential equation calibrating s to the average R&D intensity during the transition. Then, the solution to this equation takes the form

$$\gamma_A(t) = \left[C_1 e^{\int_0^t (r(v) - \gamma_Y(v) - \gamma_s(v))\, dv} - \left[\frac{\eta - 1}{\eta}\frac{\alpha(\psi_N + \psi)}{s\psi_N} - \left(1 + \frac{\psi}{\psi_N}\right)\right]\int_0^t e^{\int_v^t (r(\tau) - \gamma_Y(\tau) - \gamma_s(\tau))\, d\tau} d\tau\right]^{-1}$$

For illustrative purposes, suppose that the term $(r(v) - \gamma_Y(v) - \gamma_s(v))$ is constant. Then this expression is equal to

$$\gamma_A(t) = \left[\tilde{C}e^{(r - \gamma_Y - \gamma_s)\, t} + \frac{\left[\frac{\eta-1}{\eta}\frac{\alpha(\psi_N+\psi)}{s\psi_N} - \left(1 + \frac{\psi}{\psi_N}\right)\right]}{(r - \gamma_Y - \gamma_s)}\right]^{-1}$$

In the long run $(r - \gamma_Y - \gamma_s) > 0$, therefore for a steady state to exist, it is necessary that $\tilde{C} = 0$. This implies that

$$\gamma_A = \frac{r - \gamma_Y - \gamma_s}{\left[\frac{\eta-1}{\eta}\frac{\alpha(\psi_N+\psi)}{s\psi_N} - \left(1 + \frac{\psi}{\psi_N}\right)\right]}. \tag{34}$$

In figure 1, we can observe an upward trend in s for the post-war period. This positive growth in s, yields a lower γ_A in expression (34) than if it had remained constant.[23] Intuitively, a (temporary) upward trend in the share of resources devoted to R&D is due to an expected appreciation in the value of innovations. Therefore the current market price of innovations is higher and, from free entry, the associated growth rate of R&D driven-technology must be lower.

[23] From expression (15), it follows that, when we take into account the transition of the US during the post-war period, the resulting R&D contribution to productivity growth is also lower than if we assume that the US economy is in steady state.

4.3.1 Relationship to Jones [2001]

In a recent paper, Jones [2001] also analyzes the sources of growth in the US post-war experience and concludes that most of the growth in TFP can be accounted for by R&D. Interestingly, the basic models underlying Jones's and my analysis are the same. The difference in our conclusions resides in the different approaches followed in the quantitative analysis of the model. Instead of exploiting the free entry condition, Jones [2001] poses a production function for new technologies that he estimates to figure out how much growth can be attributed to R&D. In particular, he considers the specification reproduced in equation (35) where H_A is the number of workers in the R&D sector, and both λ and ϕ are smaller than 1.

$$\frac{\dot{A}}{A} = \hat{\delta} H_A^{\lambda} A^{\phi - 1}. \tag{35}$$

$$Y = A^{\sigma} K^{\alpha} L^{1-\alpha} \tag{36}$$

Expression (35) coupled with the Cobb-Douglas production function for final output presented in expression (36) imply an average contribution of R&D to TFP growth that is approximately equal to $\vartheta \gamma_{H_A}$, where $\vartheta = \frac{\sigma}{1-\alpha}\frac{\lambda}{1-\phi}$. It is transparent in this expression that Jones's conclusions follow from the specification used for the R&D technology and from the calibration of ϑ. Jones calibrates ϑ by estimating a log-linear approximation of (35) where A is imperfectly measured by the total factor productivity (B) as shown in equation (37).

$$\log B_t = \log A_t + \epsilon_t \tag{37}$$

More specifically, Jones estimates the following equation

$$\Delta \log B_{t+1} = \beta_0 + \lambda \gamma_B \left[\log H_{At} - \frac{1}{\vartheta} \log B_t \right] + \varepsilon_{t+1}, \tag{38}$$

where $\varepsilon_{t+1} \equiv \triangle \epsilon_{t+1} + \frac{\lambda \gamma_B}{\vartheta} \epsilon_t$ is a serially correlated error term.

As Jones points out, the estimation of equation (38) creates as many difficulties as the regressions in the productivity literature. In particular, the estimate of $\frac{1}{\vartheta}$ is likely to be biased for at least two reasons. First, business cycle fluctuations in R&D expenditures imply that the regressor is endogenous. Second, the measurement error in A (and the potential misspecification of the R&D

production equation) also generate a correlation between the error term (ε_{t+1}) and the regressor ($\log B_t$). However, Jones appeals to the possible cointegration between $\log H_{At}$ and $\log B_t$ which imply that the OLS estimate of $\frac{1}{\vartheta}$ is superconsistent (Hamilton [1994]).

An important practical issue is whether this asymptotic result can be invoked in a finite sample application like Jones's. Campbell and Perron [1991] study this question using Monte Carlo analysis and conclude that a useful rule of thumb is that asymptotic results can be exploited in samples of the size encountered in empirical applications when we can reject the null of no cointegration using the asymptotic critical values.

Table 2 presents results of an augmented Dickey-Fuller test on the residuals of the following regression:[24]

$$\log H_{At} = \alpha_0 + \alpha_1 \log B_t + u_t$$

Table 2: Cointegration regression

Dependent Variable	$\hat{u}_t$
$\hat{\beta}_0$	0.0031 (0.0089)
$\hat{\rho}$	0.804 (0.085)
R^2	0.66
N	43
Dickey-Fuller t-statistic: $(\hat{\rho} - 1) / \hat{\sigma}_{\hat{\rho}}$	-2.3

Source: http://emlab.berkeley.edu/users/chad/Sources50.asc

Robust standard errors in parenthesis.

The critical value for this statistic at the 5 percent significance level is -3.42, which is lower than the Dickey-Fuller t-statistic. Therefore we cannot reject the null that there is no cointegration between $\log H_{At}$ and $\log B_t$. While this statistical tests does not altogether rule out the possibility that $\log H_{At}$ and $\log B_t$ share a common trend, they do suggest that it may be difficult to exploit the asymptotic properties of cointegration systems in samples of the size we currently have in order to

[24] I have experimented also with several lag structures in the first differences of the residuals but these were never significant. The results of the test were always robust to such variations.

calibrate ϑ, and that exploring alternative approaches may be useful. This paper has presented one such alternative which implies a value of ϑ around 0.05 which is lower than the typical calibration in Jones [2001].

5 Welfare

So far I have conducted a positive analysis of the contribution of R&D to productivity growth. However, the previous findings can be used to conduct a normative analysis. In particular, we can proceed in the following three steps. First, specify a production function for innovations; second, use the computed growth rate of R&D-driven technology (γ_A) to quantify the size of the externalities in the production of new technologies. Finally, solve the social planner's problem and determine the socially optimal R&D intensity (s^*).

Note that in contrast to the positive analysis, now it is necessary to specify a production function for new technologies, therefore our results will depend on the particular functional form specified. In this sense, this section just intends to compare our approach to previous ones. To this end, we adopt the R&D technology used by Jones and Williams [2000] which generalizes the innovation technology posed in Stokey [1995]. Specifically, they assume that

$$\dot{A}_t = \delta \frac{1}{1 + \psi/\psi_N} R_t^{\lambda} A_t^{\phi}, \tag{39}$$

where both λ and ϕ are bounded above by 1. In steady state,γ_A is constant, therefore

$$\frac{\gamma_A}{\gamma_Y} = \frac{\lambda}{1 - \phi}. \tag{40}$$

Expression (40) relates the size of the R&D externalities to the actual growth rate of the US economy and to the growth rate of R&D-driven technology that I have already quantified in section 4.2.

Following Jones and Williams [2000], I consider a production function for final output that displays static externalities. As in section 4.2, I relate the size of this externality to the elasticity of substitution across different varieties and to the importance of embodied productivity growth. In particular, output is produced according to expression (41).

$$Y_t = A_t^{\tilde{\sigma}} Z_t K_t^{\alpha} L_t^{1-\alpha} \tag{41}$$

From section 4.2, we know that, in this context, the growth rate of R&D technology (γ_A) is given by expression (42) where $\sigma = \rho\tilde{\sigma}/\left(1 - \alpha\rho\right)$.

$$\gamma_A = \frac{r - \gamma_Y}{\left(\frac{\left(\frac{\eta-1}{\eta}\right)\alpha}{s}\left(1 + \frac{\psi}{\psi_N}\right) - 1\right)\left(\frac{\sigma-\alpha\rho}{1-\alpha\rho}\right) - \frac{\psi}{\psi_N}} \tag{42}$$

Expressions (40) and (42) define a relationship between λ and ϕ for given (η, α, s, r, γ_Y, ψ/ψ_N, ρ, σ), where these parameters can be calibrated in the decentralized economy. Table 3 summarizes this calibration.

Table 3: Parameters

r	0.07
γ_Y	0.034
α	0.33
s	0.02
ψ/ψ_N	0.25
ρ	$1/(\eta\alpha)$
σ	$\{0.9, 0.95, 1, 1.05\}$
η	1.2

There are a few remarks worth making about this calibration. First, note that the markup η is calibrated conservatively, and that I impose monopolistic pricing of the innovations in order to calibrate the elasticity of substitution across different varieties. Finally, note that in each technological cluster there are four times as many completely new goods as new versions of old goods.

Figure 10 plots the size of the R&D externality (ϕ) associated with various levels of the static externality (σ) and with the size of the stepping on the toes effect $(1-\lambda)$. This relationship is quite robust to the variation of the rest of the parameters and in this benchmark I have chosen values of η, ρ, ψ/ψ_N and θ that yield a higher schedule for ϕ.

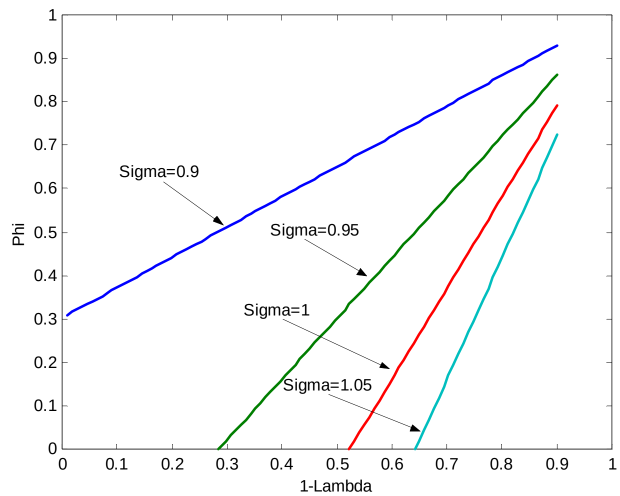

Figure 10: $\phi(1-\lambda)$

Now that we have bounded the R&D technology using actual US data, we can solve the Social planner's problem to determine the optimal R&D intensity (s^*).

Her problem can be formalized as follows:

$$\max_{\{c_t,R_t\}} \int_0^\infty \frac{c_t^{1-\theta}-1}{1-\theta}\, e^{-\varsigma t}dt$$

subject to:

$$\begin{aligned}
c_tL_t + I_t + R_t &= Y_t = A_t^{\tilde{\sigma}} Z_t K_t^{\alpha} L_t^{1-\alpha} \\
\dot{K}_t &= I_t, K_0 > 0 \\
\dot{A}_t &= \delta \frac{1}{1+\psi/\psi_N} R_t^{\lambda} A_t^{\phi},\ \ A_0 > 0 \\
\frac{\dot{Z}}{Z} &= \gamma_Z;\ \ Z_0 > 0 \\
\frac{\dot{L}}{L} &= n;\ \ L_0 > 0
\end{aligned}$$

After setting up the Hamiltonian and deriving the first order conditions it is easy to see that in steady state, the social planner devotes a share of output s^* to R&D investments, and this results in a growth rate γ_A^* of R&D-driven technology, where the expressions for these two variables are as follows:

$$\begin{aligned}
s^* &= \tilde{\sigma}\lambda \left[\frac{(1-\phi)}{\lambda}\left[\theta+\phi-1\right] + \frac{\varsigma - n(\theta-1)}{\gamma_A^*} \right]^{-1} \\
\gamma_A^* &= \frac{(1-\alpha)}{\frac{1-\phi}{\lambda}(1-\alpha)-\tilde{\sigma}} \left[n + \frac{\gamma_Z}{1-\alpha} \right]
\end{aligned}$$

To compute s^* I just have to calibrate some parameters that I have not quantified yet. These are γ_Z, ς, θ. In this model, Z is exogenous. Therefore it is reasonable to assume that γ_Z is the same in the decentralized and in the planned economy. The production function implies that in steady state, $\gamma_Z = (1-\alpha)(\gamma_Y - n) - \tilde{\sigma}\gamma_A$.

ς and θ determine the consumer preferences. The optimal consumption path for the representative consumer in the decentralized economy must satisfy the following Euler equation.

$$\gamma_c = \frac{1}{\theta}[r - n - \varsigma] \qquad \text{(Euler Equation)}$$

The growth rate of the labor force in the US in the post-war period (n) has been equal to 0.0144 and the growth rate of consumption per capita (γ_c) has been 0.021. Therefore if we calibrate the discount rate (ς) to 0.04, the Euler equation implies an inverse of the elasticity of intertemporal substitution (θ) between 1 and 2.

Figure 11 plots the resulting optimal R&D intensities for several values of σ and for the $\lambda' s$ that yield a ϕ in the interval [0,1]. The most striking fact from this figure is that the optimal R&D intensities are not much higher than the actual ones. This finding is robust to alternative parameterizations of θ, ς, σ, and of the parameters that determine γ_A.

Kortum [1993] has estimated λ to be between 0.1 and 0.6. Interestingly, for this range of λ, the actual R&D intensity roughly coincides with the intensity that the social planner prescribes.

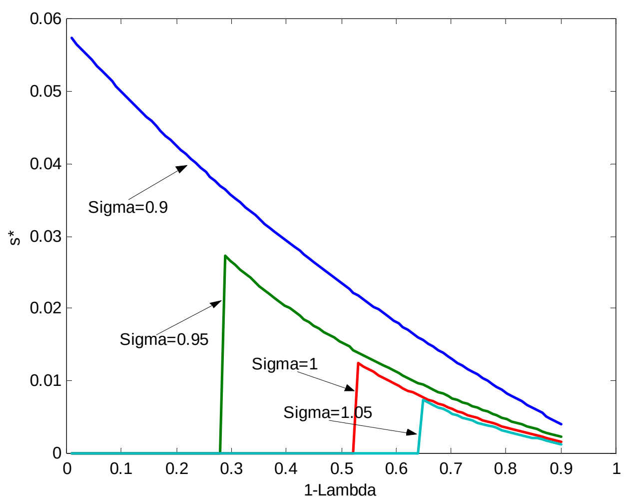

Figure 11: $s^*(1-\lambda)$

This conclusion contrasts with Jones and Williams [2000] who find that "the decentralized economy typically underinvests in R&D relative to what is socially optimal". The reason for the divergence in our findings is that we pursue different strategies to quantify γ_A. While Jones and Williams assume that all TFP growth can be explained by R&D-driven investments, this paper allows the free entry condition to determine the magnitude of γ_A.

6 Where does this leave us?

Productivity increases because we learn how to use our factors more efficiently. This learning may be a by-product of other activities not directed at increasing the productivity of resources or the result of investment efforts directed towards the improvement of productivity. In this paper I have focused in evaluating the contribution to productivity growth of one of these investments, R&D. From the free entry condition into R&D and the fact that R&D innovations are embodied in the sense of Solow [1959], I have shown that R&D is not responsible for a large share of productivity growth in the US. Since the US is the world leader in R&D, this conclusion can be made extensive to the other nations.

Our prior was that R&D is the main source of long run growth. The immediate question that emerges from this analysis is "then, what is the driving force of productivity growth?". This question should be placed at the top of the research agenda.

I would like to stress that the relatively minor contribution of R&D to productivity growth found in this analysis does not imply in any way that other purposeful investments (management, organization, personnel, financial engineering, and many others) directed to improve productivity are not very important. There are indeed two reasons to anticipate an important contribution from these non-R&D investments. First, the size of the expenditures in these other activities is probably one order of magnitude larger than R&D expenditures. Second, since the innovations that result from these investments are disembodied, not patentable and quite easy to imitate, the externalities associated with them are probably much larger.

From a normative perspective, the analysis conducted in this paper implies that the decentralized economy may not be underinvesting in R&D.

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