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# IS FINANCIAL SUPPORT FOR PRIVATE R&D ALWAYS JUSTIFIED?
# A DISCUSSION BASED ON THE LITERATURE ON GROWTH

Benjamin Montmartin* and Nadine Massard†

**Abstract**

Many economists have long held that market failures create a gap between social and private returns to Research and Development (R&D), thereby limiting private incentives to invest in R&D. However, this common belief that firms significantly underinvest in R&D is increasingly being challenged, leading the rationale behind public support for private R&D to be questioned. In this paper, we attempt to clarify the perspectives of two sources: the theoretical literature on endogenous growth, and its recent developments in integrating a geographical dimension, and the empirical literature that measures the social returns to R&D in relation to the private returns. Ultimately, we are able to clearly distinguish among different types of market failures and compare their relative impact on the gap between the private and social returns to R&D. Two main conclusions are reached. First, systematic firm underinvestment in R&D is not demonstrated. Second, even though instances of underinvestment do occur, they are mainly explained by surplus appropriability problems rather than by knowledge externalities. This suggests the need for a new policy mix that employs more demand-oriented instruments and is more concentrated on identifying efficient allocations among activities rather than merely increasing global private R&D investment.

**JEL Classification: E61, 041, O38, R11**

**Keywords: Returns to R&D, Market failures, R&D-based growth, Economic Geography, R&D policy**

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## Introduction

In most countries, investment in R&D is considered to be crucial for innovation and thus for future growth and competitiveness. Consequently, many countries have set ambitious targets for investment in R&D. For example, among the five targets defined by the Europe 2020 strategy for growth[1] is a goal of investment in R&D of 3% of EU GDP (2/3 of which should be realized by private funding). All OECD countries have also set such targets.

Moreover, these global strategies are generally informed by the idea that private incentives to invest in R&D are insufficient because of the specific attributes of such activities. Indeed, although R&D investment usually requires a large amount of financing and is highly risky, it is also irreversible and rarely profitable in the short run. The public-good attributes of the knowledge produced by R&D also imply that potential external effects are not incorporated into the economic calculations of firms when they make investment decisions.

In the economics literature, the implications of these attributes on private incentives to invest in R&D have been widely studied. Such attributes generate sources of market failures that create a theoretical gap between private and social returns to R&D. Although some characteristics of R&D investment would lead firms to overinvest in R&D compared to the socially optimal level of investment, there is broad consensus that the negative effects of market failures on private investment in R&D are generally dominant.

It is worth noting that, based on this consensus, belief in the global underinvestment of firms in R&D has rapidly become widespread among public authorities, so much so that it is currently often taken for granted and considered to justify the implementation of many public policies aimed at supporting R&D activities within firms. Such policies seek to not only establish a favorable institutional context for R&D investment (notably based on the patenting system), but increasingly to direct financial subsidies or indirect tax credits to firms to support R&D.

All countries within the OECD, for example, provide direct financial support for R&D and the number of OECD countries providing indirect financial support has grown from 12 in 1996 to 21 in 2008 (Mohnen and Lokshin, 2009). Among those countries implementing a combination of direct and indirect support, a tendency seems to be emerging whereby direct support is being progressively replaced by indirect support. Nevertheless, the volume of funding devoted to direct support has greatly increased since the 1980s (Montmartin, 2013), and this is even more true in the case of indirect support.

However, this commonly held belief in the widespread under-investment of firms in R&D relative to the socially optimal level is increasingly being questioned. Such questioning is motivated by various factors. From a political perspective, increasing tensions within the public sector generated by the financial crisis have reinforced the need to strongly justify and rigorously evaluate public expenditures. Additionally, a review of the economics literature in the field reveals significant weaknesses in both the theoretical and empirical bases for the belief in widespread underinvestment in R&D. On the theoretical front, new analyses questioning the importance, and even the existence, of firm underinvestment in R&D have recently been published. On the empirical front, the weaknesses of existing empirical measures of the social return to R&D have cast doubt on the consensus that social returns to R&D exceed private returns.

Moreover, given available data on the volume of private investment in R&D, the capacity of already implemented public policies to actually produce the expected incentive effects may be reasonably questioned. Indeed, R&D financed by the private sector within the European Union has increased only minimally over the last decade, rising from 1.03% of GDP in 1999 to 1.09% in 2009, while in many countries, the cost of national public support for R&D activities has increased significantly, along with the financial endowments of European programs (essentially through R&D Framework Programs, but also more recently through regional policies). Similarly, it may be noted that the European countries in which private investment in R&D is close to or above the objective of 2% of GDP are also the countries in which public financial support for private R&D is rather low (lower than the European and OECD averages).

Given increasing tension around public expenditures, the availability of relevant methodologies to evaluate the impact of the public policies implemented to support private R&D investment is becoming increasingly important for policy makers as they decide upon and design suitable policy instruments. In observing current practices and public policy choices made over the last several years and analyzing the conclusions of primary evaluations of these policies, we are left, however, with a rather fuzzy picture that makes it difficult to generate sound expectations regarding what the implemented policies will achieve.

In our view, two main factors contribute to the ambiguities in the implications of the evaluations that have been conducted to date:

• First, the fact that all the policies are based on the taken-for-granted assumption of private firm underinvestment in R&D.

• Second, the fact that although public policies aimed at encouraging firms to invest more in R&D are diverse, they are generally designed and evaluated separately.

Within this context, a better understanding of the effects of various types of market failures on the incentives of private agents to invest in R&D becomes important. It will help to precisely characterize situations in which differences between social and private returns to R&D arise and design public policy instruments that are capable of correcting the relevant market failures. Moreover, a thorough analysis of the impact of market failures on R&D and the sources of these market failures would provide a much sounder basis for the evaluation of public policies designed to encourage R&D while providing better estimates of the extent of private sector underinvestment in R&D and the potential effects of various policy mixes (using various instruments to correct various market failures) on R&D investment.

The objective of this paper is to investigate the notion of firm underinvestment in R&D using the theoretical framework provided by the endogenous growth literature and its refinements, including its integration with economic geography models. This extensive field in the economic literature, which places innovation and investment in R&D at the heart of the growth process, is a particularly suitable framework for this discussion. It will allow us to precisely identify the main sources of market failure, characterize their effects (positive or negative) on incentives for firms to invest in R&D and identify suitable financial instruments to correct them. In doing so, we will be able to provide a comprehensive, clear and concise overview of the origins and impact of various types of market failures on R&D, as well as solutions to these problems.

Five different sources of market failure are identified. One of these clearly leads private agents to underinvest in R&D, whereas two others lead them to overinvest. The two remaining sources, which are related to knowledge externalities and economic geography, have ambiguous effects. Thus, our review of the literature on growth shows that various types of market failures have opposing effects on private incentives to invest in R&D; therefore, we are ultimately unable to reach a specific conclusion regarding the existence of widespread underinvestment in R&D by private firms. Facing this theoretical inconclusiveness, we searched for clarification in the empirical literature that documents and measures private sector underinvestment in R&D. After demonstrating the limitations of this research, based on estimated extended innovation production functions, we looked to studies that calibrate theoretical models. These not only take diverse theoretically identified types of market failures into account, but also estimate their relative importance, which may have significant implications for public policy. Whereas the pioneering papers of Jones and Williams (1998, 2000) conclude that firms significantly underinvest in R&D, the more recent calibration exercises of Comin (2004), Alvarez-Pelaez and Groth (2005), Reis and Sequeira (2007) and Strulik (2007) strongly qualify this conclusion. Overall, their arguments tend to cast doubt on the idea of the massive, global insufficiency of private investment in R&D. Private sector underinvestment in R&D is seen as occurring only in specific contexts.

The remainder of this paper is organized as follows. Section 1 presents the evolution of the modeling of R&D and innovation, from the first generation of endogenous growth models to models that integrate R&D into an economic geography framework, with a specific focus on the types of market failures that are identified by these models and the potential for public policies to address them. Section 2 provides more detailed descriptions of the origins and impacts of the main types of market failures identified here, as well as measures that could potentially correct them. Section 3 discusses whether private sector underinvestment in R&D actually exists in light of econometric and calibration exercises that seek to measure the gap between private and social returns to R&D. Our main proposals regarding the use of financial instruments in public policies and avenues for future research are developed in the conclusion.

# 1 R&D, innovation and growth: Theoretical modeling and the role of public policy

## 1.1 From a "productivity black-box" framework to a R&D productivity enhancing framework

The renewal of growth theories at the end of the 80s and the beginning of the 90s sought to address criticisms of neo-classical growth models à la Solow (1956), which are the assumptions of an exogenous savings rate and exogenous technological progress. These assumptions, combined with a cumulative factor exhibiting diminishing returns to scale, imply that the long-run growth rate of the economy is equal to the exogenous rate of technological progress. Consequently, governments cannot influence the steady-state growth rate of the economy through incentive measures. Some growth models, such as those of Lucas (1988) and Rebelo (1991), partially respond to these criticisms by making the savings rate endogenous and allowing for sustained growth (without technical progress), assuming constant returns to the cumulative factor. Although such models are interesting because they highlight (1) the conditions necessary to obtain a positive growth rate in the long run without technical progress (the accumulated factor should exhibit constant returns to scale), (2) the existence of external capital effects that can explain sustained growth and (3) the need for government interventions when capital externalities exist, major dissatisfaction remains. Indeed, the models of Lucas (1988) and Rebelo (1991) postulate the exogeneity of technical progress, i.e., they do not explain the origins of Total Factor Productivity (TFP). In other words, such endogenous growth models are only useful for exploring the determinants of growth that are not related to innovation.

This theoretical limitation was a major concern for economists because most empirical studies indicate a significant contribution of TFP to economic growth (and it is perhaps the most important contribution). The previously cited models are not able to endogenously explain TFP because they are constructed using a perfectly competitive market framework. According to Romer (1990), the ideas and knowledge that are at the root of innovation share the characteristics of public goods (meaning that they are non-rival and non-excludable), which suggests that technical progress cannot occur in a context of perfect competition. The models of Romer (1990), Grossman and Helpman (1991) or Aghion and Howitt (1992), which macroeconomists refer to as the first generation of R&D-based endogenous growth models, respond to this problem by introducing an imperfect competitive framework. In these models, the existence of an imperfect competitive market is related to the presence of an intellectual property system that provides infinite-life patents to inventors. This patent system creates an incentive for inventors to perform R&D activities with the objective of launching new products and processes to benefit from (relative) monopoly power. In this way, and in contrast to the models of Solow, Lucas and Rebelo, these models explain the origins and evolution of TFP as the result of (individual) rational decisions.

In the next subsection, we will describe how the R&D-based growth literature (since the 90s) has modeled the origins and evolution of the TFP and try to highlight (1) the core debates that have emerged and (2) their public policy implications. This literature is summarized in Table 1 at the end of the paper.

## 1.2 From the first-generation of R&D-based growth model to the second and beyond: Literature in support of public R&D policies

### 1.2.1 The first generation of R&D-based growth models

The first generation of R&D-based growth models proliferated in the 90s following the pioneering works of Romer (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992). This literature explains the evolution of technical progress by the research efforts conducted by entrepreneurs. The nature of innovation is the main element of differentiation in this literature. Two main classes of innovation are modeled: the introduction of new (varieties of) products and/or quality improvements to existing products. This distinction is fundamental for the R&D-based growth literature due to strong differences in terms of (1) modeling, (2) implications and (3) scientific development. In what follows, we briefly present the general properties of these two strands of the growth literature.

**Growth models based on the creation of new products**

In these models (see Romer (1990) and Grossman and Helpman (1991, chap.3)), the level of the economy's technical progress is determined by the number of (differentiated) intermediate available products that are used in the production of a final consumption good. Thus, the evolution of TFP is determined by the arrival rate of new products. Increased productivity in such models can be interpreted as follows: every intermediate product achieves one particular goal of the production process such that the creation of new intermediate products leads to an increase in the specialization and rationalization of the production process. We can summarize the core elements of such models with the following equation:

$$Y_t = \left[ \int_0^{A_t} x_{it}^{\sigma} di \right] \tag{1}$$

where $Y_t$ represents the final consumption good, $A_t$ is the number of varieties, $x_{it}$ is the quantity of intermediate products $i$ used in production and $\sigma \in ]0;1[$ represents the degree of substitution between each intermediate product. In such models, the creation of new intermediate products is carried out in two steps: first, entrepreneurs have to undertake R&D efforts to create blueprints of the new products before being able to put them into production (and enter into monopolistic competition). Note that in such models, incentives to perform R&D are primarily attributable to the existence of an IP system that provides infinite-life patents to inventors, which ensure that they will be "local" monopolists in the production of their products. The arrival rate of blueprints (hereafter referred to as "knowledge") is assumed to be a deterministic function of R&D efforts and past knowledge level:

$$\dot{A}_t = \delta A_t a L_t \tag{2}$$

where $A_t$ represents the existing knowledge stock and is equal to the number of varieties, $0 < a < 1$ represents the proportion of workers engaged in R&D activities, $L_t$ is the quantity of labor and $\delta$ is an exogenous R&D productivity parameter. This knowledge production function reflects the notion of Romer (1990) that the quasi-public-good characteristics of knowledge imply that all entrepreneurs have access to the global knowledge stock. Consequently, the existing knowledge stock generates positive external effects for all potential innovators.

The steady state of such models is characterized by a constant TFP (hereafter referred to as "growth") rate denoted by $g = \dot{A}_t/A_t$. As seen in (**??**), the growth rate increases with the number of researchers ($L_t$) such that according to such models, the higher the number of researchers in an economy, the higher the growth rate is. In contrast to the models of Solow, Lucas and Rebelo, this implies that the implementation of public support for R&D would be able to influence an economy's long-run dynamics. Although an expansion in the variety of products used in production captures certain aspects of the innovation process, most innovations we observe in practice either increase the quality of an existing product or reduce production costs. Therefore, numerous innovations have a number of distinct features compared to "horizontal" differentiation.

#### Growth models based on the quality improvement of existing products

In these models (see Grossman and Helpman (1991, chap.4) and Aghion and Howitt (1992)), the level of the economy's technical progress is determined by the quality level of the intermediate products that are used in the production of a final consumption good. Thus, the evolution of TFP is determined by the arrival rate of higher quality intermediate products. Increased productivity in such models is related to the quality of an intermediate product, which determines its level of productivity in the final good production sector. We can summarize the core elements of such models with the following equation:

$$Y_t = \sum_{i=1}^{m} A_{it}^{1-\sigma} x_{it}^{\sigma} \tag{3}$$

where $Y_t$ represents the final consumption good, $x_{it}$ is the quantity of intermediate products $i$ used in the production and $A_{it}$ is a productivity variable that measures the quality of each input $i$. Thus in such models, the productivity growth of the economy is the sum of the productivity growth in each $i$ intermediate product sector. Each intermediate product $i$ is produced and sold exclusively by the most recent innovator. A successful innovator in sector $i$ improves the quality parameter $A_{it}$ by a factor $\gamma > 1$ and is thus able to displace the previous innovator as the incumbent intermediate monopolist in that sector, until being displaced by the next innovator. If technological progress is driven by R&D efforts of entrepreneurs and the knowledge stock available in the economy, as in the previously presented product variety model, the arrival rate of a new quality product in sector $i$ is sometimes assumed to be random:

$$A_{i,t+1} = \begin{cases} \gamma A_{i,t} & \text{with a probability } \delta a L_t \\ A_{i,t} & \text{with a probability } 1 - \delta a L_t \end{cases} \tag{4}$$

where $aL_t$ represents the number of researchers working in R&D when the quality $A_{it}$ of product $i$ is the "leading-edge" technology, i.e., the required investment in R&D to generate the next quality level. Note that these models implicitly include intertemporal knowledge externalities in the sense that the inventor of the $A_{i,t+1}$ quality level freely uses the knowledge embodied in past quality levels $A_0, A_1, ..., A_t$. The steady state of such models is characterized by a constant growth rate, denoted by $g = \dot{A}_t/A_t$, and supported by the continuing appearance of innovations, which increase the productivity of the final sector. According to the innovation production function (4), the long-run growth rate has the same relation with the R&D input as in the expanding variety models. Consequently, public policies raising private incentives to invest in R&D are able to increase the long-run growth rate.

Thus, the main contribution of the quality ladder models (compared to the variety models) is the introduction of a creative destruction process of innovation. Indeed, such a process is absent in the expanding variety models, in which a newly invented product is used alongside all previous product varieties; in practice, newly invented, superior products often replace existing varieties. Thus, in some sense, expanding product variety models do not provide a good description of innovation dynamics in practice because they do not capture the competitive aspects of innovation. These competitive aspects are related to the Schumpeterian creative destruction process in which economic growth is driven, at least in part, by the replacement of incumbents by new firms. Nevertheless, although the nature of innovations differs from (and, in certain sense, is complementary to) expanding variety models, their fundamental conclusions are relatively similar[2]. Indeed, in both classes of models, the long-run growth rate is primarily driven by rational private investment in R&D, which allows public authorities to implement incentive systems that will influence the economy's dynamics.

### 1.2.2 The scale effect debate and the second generation of R&D-based growth models

During the 90s, an intense debate concerning the first generation models emerged and has been the "fuel" for the development of the second generation of models. This debate concerns the existence of a strong scale effect in these models, which constitutes an important limitation for many economists, such as Jones (1995a). Indeed, as previously mentioned, in such models, the TFP dynamics is directly dependent on the amount of resources allocated to R&D activities. This implies that the size of an economy's population, given preferences and technologies, is the main driver of its growth rate. In other words, this scale effect means that if an economy grows by 100%, the resources allocated to R&D, and subsequently its growth rate, should also increase by 100%. Obviously, this implication is not verified in reality, as indicated by Jones (1995b, p.760): "The number of scientists engaged in R&D in advanced countries has grown dramatically over the last 40 years and growth rates either have exhibited a constant mean or have declined on average."

The pioneering work of Jones (1995b) attempts to avoid this scale effect while retaining the core elements of first-generation models. This scale effect is caused by the fact that the used innovation production function (see ((**??**) and (**??**)) exhibits constant returns to R&D (measured by the ratio $\dot{A}_t/aL_t$). The model of Jones (1995b) is very similar to that of Romer, with the exception of the innovation production function:

$$\dot{A}_t = \delta(aL_t)^{\lambda}A_t^{\epsilon} \tag{5}$$

where $\epsilon < 1$ represents the degree of intertemporal knowledge externalities, $\lambda \in ]0,1]$ refers to the existence of duplications in R&D activities and the other parameters have the same meaning as previously. Because $\epsilon < 1$, this innovation production function exhibits diminishing returns to R&D. For Jones (1995b), the degree of spillovers is determined by two opposing effects. The first reflects the idea that knowledge accumulated in the past increases the productivity of current R&D activities. The second refers to the concept of "lower technological opportunities", which means that the greater the knowledge stock, the greater the difficulty of creating new knowledge. Note that when $\epsilon = 1$ and $\lambda = 1$, we obtain the innovation production function used in the first generation of variety growth models (2). Thus, the innovation process modeled in Romer (1990) or Grossman and Helpman (1991) is a particular case in which returns to R&D are constant, which is not justified a priori according to Jones (1995b)[3]. The assumption of decreasing returns to R&D retained in the model of Jones implies that the growth rate becomes independent of investment in R&D in the long run. At first glance, this result has strong implications for public interventions in the sense that public policies that increase incentives to invest in R&D will only have a temporary effect on the growth rate. Indeed, because accumulated capital (in this case knowledge) exhibits diminishing returns to scale, the dynamics of this model has the same properties as the model of Solow, that is, the long-run growth rate is primarily driven by the population growth rate. Consequently, as mentioned by Jones (1995b), such a model cannot be classified as endogenous because long-run growth is not dependent on the rational decisions of economic agents. Nevertheless, the evolution of TFP, which generates the long-run growth rate, is the consequence of R&D activities realized by rational agents. This is the reason why this type of model is usually considered to be "semi-endogenous". Kortum (1997) and Segrestrom (1998) have adapted the semi-endogenous growth process into a quality-improving innovation framework.

The semi-endogenous literature represents, however, only a particular strand of the second generation of R&D-based growth models. In the late 90s, several authors, such as Aghion and Howitt (1998, chap.12), Peretto (1998), Young (1998) and Dinopoulos and Thompson (1998), developed new methods for eliminating the scale effect while maintaining an endogenous growth pattern, which we refer to as Schumpeterian growth models. These models add a second dimension to the first-generation R&D-based growth models. To simplify, they assume that there are two types of R&D. The first type creates blueprints for horizontally differentiated goods, and their quality is improved through the second type of R&D. In other words, in these models, the level of technical progress is determined by both the number and quality of the available intermediate goods used in the production of a final consumption good. Thus, the evolution of TFP is determined by the arrival rates of new products but also by improvements in the quality of these intermediate goods. Even if this class of models presents technical complications, we can summarize its core elements with the following equation:

$$Y_t = \left[ \int_0^{A_t} x_{it}^{\sigma} di \right]^{1/\sigma} \tag{6}$$

where $Y_t$ represents the final consumption good, $x_{it}$ is the quantity of intermediate products $i$ used in production and $A_t$ is the number of varieties of the intermediate product. As before, $\sigma \in ]0;1[$ represents the degree of substitution between each intermediate product. The arrival rate of new varieties is assumed to only be a deterministic function of the R&D efforts[4]:

$$\dot{A}_t = aL_t \tag{7}$$

where $a$ represents the proportion of workers engaged in the R&D activities to develop new varieties. Remember that there is a second type of R&D that improves on the quality of the intermediate output used in the final good sector. There are $(1-a)L_t$ workers available to improve quality and produce $x_{it}$ goods. Assuming that a fraction $(1-b)$ of them are employed in the production of $x_{it}$, then we can express the production function of $x_{it}$ as:

$$x_{it} = B_{it} \frac{(1-b)(1-a)L_t}{A_t} \tag{8}$$

where $B_{it}$ is the level of quality of the $x_{it}$ goods. The remaining fraction of workers is employed in the second type of R&D and we assume that the quality of good $i$, denoted $B_{it}$, evolves according to:

$$\dot{B}_{it} = \delta \frac{b(1-a)L_t}{A_t} B_{it} \tag{9}$$

Note that in contrast to the first type of R&D, the second type of R&D (quality enhancement) allows for intertemporal knowledge externalities in the sense that past quality increases the productivity of this type R&D. It is straightforward that the long-run growth rate of the economy is a linear function of the evolution of the number and quality of varieties. According to (7), the long-run growth of new varieties is pinned down by population growth (as in semi-endogenous growth). According to (8), the evolution of quality is a function of population growth but is not pinned down by it because the dynamics of quality is affected by the proportion of workers used in both types of R&D, which is endogenously determined. It should also be noted that this model eliminates the scale effect because the growth rate does not depend on population size but rather on the intensity of labor employed in both R&D sectors. Consequently, and in contrast to semi-endogenous models, this type of model offers new opportunities for public interventions. Indeed, public policies that increase private incentives to invest in R&D are able to increase the long-run growth rate by changing the allocation of workers between R&D and production. The reason that the scale effect disappears is that when the population increases, the number of available varieties increases proportionally, leaving the amount of research per variety, and therefore growth, unchanged. Because the Total Factor Productivity in those models has two dimensions, such models appear to be more realistic and empirical data seem to confirm this idea. Indeed, the empirical studies of Madsen (2008) and Saunoris and Payne (2011) suggest that the evolution of TFP is clearly better explained by research intensity (Schumpeterian models) than by the rate of population growth (semi-endogenous models). Nevertheless, according to Jones (1999), this result relies again on a special case in which labor productivity in the research sector is constant over time. In fact, in equations (7) and (9), these models implicitly assume that $L_t^{\lambda}$, where $\lambda = 1$. Jones (1999) shows that if we assume that $\lambda \neq 1$, then the model exhibits a scale effect ($\lambda < 1$) or asymptotically returns to a semi-endogenous growth model ($\lambda > 1$).

### 1.2.3 Beyond the debate on scale effects

The previous section shows that the endogeneity of the growth rate in the literature is strongly dependent on knife-edge assumptions that are subject to debate. Nevertheless, some economists, such as Temple (2003), question the importance of the scale effects issue. According to Temple (2003, p.498), "Instead of worrying about the effects of policy on the growth rate in a hypothetical long-run equilibrium, perhaps far distant in time, we should analyse the impact on welfare. It is entirely possible that models which yield very different long-run outcomes are in much closer agreement on welfare implications." His argument is based on the fact that the central question in growth theories is to understand the relationship between parameter changes and the level of welfare, not the long-run behavior of the growth rate. Indeed, although investment in R&D has no long-run effects on growth in the semi-endogenous literature, it does, however, have a direct effect on the level of per-capita income. Consequently, determining the channel through which a public policy (affecting private incentives to invest in R&D) influences welfare is not really crucial because it is not obvious that an effect on the growth rate is more effective than an effect on the income level. Indeed, if a policy that increases the growth rate has the same effect on welfare as a policy that increases per-capita income, then the debate between endogenous and semi-endogenous growth does not appear to be very relevant. The more important questions resulting from this observation are the extent to which the result of the free market equilibrium outcome differs from the optimal outcome and the public policies that are able to reach this optimum. Indeed, both the first and second generations of R&D-based growth models show that public policies that affect private incentives to invest in R&D can directly affect welfare (but not through the same channels).

In addition, although the scale effects debate was one of the main drivers of the R&D-based growth literature in the 90s, other approaches emerged in the late 90s and during the

2000s with objectives other than dealing with the issue of scale effects. Among these, we can mention the important works of Aghion et al. (1997, 2001, 2005), which gave a new momentum to Schumpeterian models by modifying the nature of technological progress. In previous Schumpeterian models, a technological laggard could never develop and use the current state-of-the-art technology; the only way for a laggard to advance is to leapfrog over the industry leader by developing a superior technology. In contrast to this view, the step-by-step approach developed by Aghion et al. (1997, 2001, 2005) assumes that laggards cannot develop superior technologies directly but are instead forced to first catch up with the leading-edge technology before battling for technological leadership in the future. This vision of technological progress provides new theoretical results with regard to the relation between product market competition (PMC) and growth. In earlier Schumpeterian models, an increase in PMC always has a negative effect on growth because it reduces the flow of monopolistic rents and hence reduces the incentives to innovate. In a step-by-step process, the incentive to perform R&D does not depend on the rents of a successful innovator but rather on the innovator's incremental rents, that is, the difference between the post- and pre-innovation rents of incumbent firms. As shown in Aghion and al. (2005), this no longer implies a negative linear relationship between PMC and innovation but rather an inverted-U-shaped relationship. The reason for this is that more competition may increase the incremental profits from innovating and thereby encourage R&D investments with the objective of "escaping innovation". Aghion et al. (2005) show that the positive relation between PMC and innovation particularly exists in sectors where incumbent firms are engaged in "neck-and-neck" competition, whereas a negative relationship is more likely to appear in sectors where incumbent firms are far from the technological frontier.

Thus, the step-by-step innovation framework provides a more realistic modeling of private incentives to invest in R&D. This highlights the possibility of a non-linear relationship between core economic variables, implying a non-linear gap between market and social outcomes. More specifically, these works show that (1) more competition can have both positive and negative effects on incentives to invest in R&D and (2) appropriate R&D support is strongly influenced by the existing link between competition and innovation, which is industry-specific and primarily depends on the technological gap between leaders and followers in a particular industry. Nevertheless, although this new development in the R&D-based growth theory is very interesting and its implications for public interventions could be discussed further, we choose to focus on another development in this literature for two reasons. The first is related to the complexity of the step-by-step approach, which does not allow for the analysis of welfare in relation to R&D policies. The second is that there is a more tractable and less known literature that integrates a very promising and important dimension of the R&D-based growth literature, namely, the role of location. Indeed, in the late 90s, new models emerged providing a synthetic framework between the New Economic Geography models (Krugman, 1991) and the endogenous growth theory (Romer, 1990). The advantage of this literature is that it provides an analytical framework reporting the stylized facts regarding the interactions between innovation, economic geography and growth. This framework is especially interesting in discussing the effects of R&D policies given the empirically observed, specific geography of innovative activities.

## 1.3 The New Economic Geography and Growth models

The New Economic Geography (NEG) models provide a theoretical explanation for the agglomeration of economic activities based on the existence of pecuniary externalities linking the locations of firms with those of consumers. These pecuniary externalities[5] result from the combination of increasing returns and transport costs that influence the trade of goods. The main contribution of this literature is that it demonstrates that such pecuniary externalities can produce self-sustaining agglomeration processes. Consequently, the advantage of crossing NEG models with endogenous growth models is the integration (in a dynamic framework) of two main stylized facts: (1) the location of economic activities is characterized by agglomeration and (2) the capital accumulation is driven by the spatial concentration of economic activities.

In terms of modeling, the New Economic Geography and Growth (NEGG) literature always uses a variety of growth process (mostly endogenous, but could also be semi-endogenous) but different location frameworks. In summary, we can group NEGG models into two categories. The first includes cumulative causation mechanisms related to the migration of labor or the vertical links between industries. The second assumes that capital is mobile but its owners are not; therefore, this location framework, called Footlose Capital (FC), excludes cumulative causation mechanisms related to demand in the Core-Periphery model (CP) à la Krugman (1991), or costs in the vertical linkages model (VL) à la Krugman and Venables (1995). Consequently, the first category of NEGG models (with a CP or VL location framework) will mainly focus on analyzing the stability of symmetric and core-periphery configurations, whereas stability issues are not present in the second category of NEGG models (with FC location framework) because each location equilibrium is stable by definition. This simpler location framework is particularly useful for analyzing the effects of public policies in an NEGG framework. The table below summarizes the contributions to the NEGG literature:

| **Core Periphery and Vertical linkage** | **Footloose Capital** |
|---|---|
| Englmann and Walz (1995) | Martin and Ottaviano(1999) |
| Walz (1996) | Martin (1999) |
| Walz (1999) | Baldwin and Forslid (2000a) |
| Baldwin and Forslid (2000b) | Baldwin, Martin and Ottaviano (2001) |
| Martin and Ottaviano (2001) | Riou (2003) |
| Fujita and Thisse (2002) | Baldwin and Martin (2004) |
| Fujita and Thisse (2003) | Minniti and Parello (2011) |
| | Montmartin (2013) |

In what follows, we briefly present an extension of Martin and Ottaviano's (1999) NEGG model, which uses a Footlose Capital location framework. In this framework, the technological level of the economy is determined, as in Romer (1990), by the number of differentiated products available. There are two countries ($i$ and $j$) that share the same technologies and preferences but can have different initial endowments of knowledge, denoted by $A_{i(0)}$ and $A_{j(0)}$, respectively. In contrast to Romer's model, these goods are not used as intermediate inputs to produce a final consumption good. Instead, they are consumption goods subject to "Iceberg trade costs" between the two countries. We can summarize the core elements of these models with the following equation:

$$Y_t = \left[ \int_0^{A_{it}} x_{it}^{\sigma} di + \int_0^{A_{jt}} x_{jt}^{\sigma} dj \right]^{1/\sigma} \tag{10}$$

where $Y_t$ represents a world consumption index for differentiated products, $A_{i(j)}$ represents the number of varieties produced in countries $i$ and $j$ respectively, and $x_{i(j)}$ represents the quantity of each variety produced. As in Romer, the intermediate firms have to engage in R&D activities to create a variety blueprint before being able to produce that variety. Consequently, in these models, the total number of varieties $A_t = A_{it} + A_{jt}$ is again strictly equivalent to the number of blueprints produced by R&D activities. The R&D sector in the model is similar to that in Romer (1990)[6] with the exception that in this case, economic geography will matter. Because knowledge is perfectly mobile across countries, the countries' growth rates are equal to the world growth rate. The arrival rate of blueprints is still assumed to be a deterministic function of R&D efforts and the past knowledge level but is also influenced by the economic geography:

$$\dot{A}_t = \delta a L_t W A_t \tag{11}$$

$$W \equiv \max\{s_n + \gamma(1 - s_n); \gamma s_n + (1 - s_n)\}$$

where $A_t = A_{it} + A_{jt}$ represents the world stock of existing knowledge, $a$ represents the proportion of workers employed in R&D, $L_t$ is the quantity of labor, $\delta$ is an exogenous R&D productivity parameter and $W$ is the space component of knowledge spillovers. $s_n \equiv A_{it}/A_t$ represents the share of intermediate firms operating in country $i$. According to the empirical literature on knowledge spillovers (Audretsch and Feldman, 1991, 2004), the parameter $\gamma \in [0, 1]$ will account for the localized nature of knowledge spillovers. Indeed, the existence of tacit knowledge, which is better transmitted by face-to-face contact, implies that geographic proximity is relevant to the transmission of knowledge. If $\gamma = 0$, then knowledge spillovers are purely localized, i.e., R&D activities located in country $i$ will only accede to the $A_{it}$ stock of knowledge whereas those located in country $j$ will only accede to $A_{jt}$ stock of knowledge. When $\gamma = 1$, knowledge spillovers are purely global; in this case, geography does not matter and we obtain innovation production (2). When $\gamma \in ]0, 1[$, knowledge spillovers are partially localized, that is, the R&D activities located in one country can only partially benefit from knowledge produced abroad. Obviously, because R&D activities are perfectly competitive, such activities will be entirely located in the country that offers the highest level of knowledge externalities, that is, the country that hosts the higher number of intermediate firms. Remember that the location of intermediate firms will depend on the interplay between increasing returns (which provides incentives for firms to locate themselves in the bigger market) and the transaction costs on goods (which provides incentives for firms to escape competition and locate themselves in the smaller market), as in New Economic Geography models.

The steady state of such models is characterized by a constant TFP growth rate, denoted by $g = \dot{A}_t/A_t$. Here, the growth rate is subject to the scale effect discussed below but this can be avoided by employing an innovation production function, as in Jones (1995b). The scale effect is not of importance here but rather the influence of the economic geography on growth. As seen in (11), as long as there is an asymmetric location equilibrium for intermediate firms, i.e., $s_n \neq 1/2$, then the higher the concentration of firms in a country, the higher the world growth rate is. This means that these models integrate two important stylized facts: (1) the economic geography directly influences the dynamics of economies and (2) there is a positive link between the concentration of economic activities and the level of growth. Consequently, this framework highlights the fact that public policies that increase incentives to innovate in R&D will not only influence welfare via scale or level effects but also via an effect on the economic geography. This shows that policy makers must define not only the total amount of support to R&D but also its geographical distribution to account for spatial effects.

After having observed the evolution of the links among R&D, innovation and growth in the R&D-based growth literature and their implications for public policy, the next section identifies the main externalities and distortions related to R&D activities. Following Temple's (2003) suggestion, we will focus on welfare issues related to R&D by studying the origins of a potential gap between the free market and optimal equilibria and by identifying the instruments that are potentially capable of filling this gap.

# 2 The R&D-related sources of market failures and public instruments that can correct them

Although it is still the source for many discussions concerning the modeling of R&D and innovation, the R&D-based growth literature that we have reviewed above raises the following central questions: To what extent could the results of a decentralized economy diverge from the social optimum? What would the origins of such divergence be and which are the most suitable policies that can be implemented to fill this gap?

In this section, we detail the main sources of market failure that have been identified by the growth literature. We notably emphasize the new types of externalities identified by the introduction of the New Economic Geography framework into endogenous growth models. For each type of market failure, we also indicate the public policy instruments that are capable of correcting them. A summary of this second section can be found in Table 2 at the end of the paper.

### 2.1 Intertemporal knowledge externalities: The "standing on shoulders" and "fishing in the same lake" effects

The existence of knowledge externalities is explained by the very nature of the knowledge generated by R&D. Indeed, knowledge displays some well-known characteristics of public goods (non-rivalry and only partial excludability) that contribute to its free diffusion to firms that have not participated in its production. Within endogenous growth models, such externalities are intertemporal, i.e., externalities produced by a firm during period $t$ will increase the global knowledge stock available at $t+1$. The theoretical literature distinguishes between two main possible effects of this increase in the knowledge stock. The first refers to the "standing on shoulders of giants" phenomenon, which is derived from the quotation by Isaac Newton and implies that the knowledge production process is cumulative: the more important the available stock of knowledge is, the easier it is for researchers to invent and produce new knowledge. The second effect, the "fishing in the same lake" phenomenon, has the opposite consequence. It states that the most obvious inventions are generated first; therefore, an increase in produced knowledge reduces future technological opportunities. According to the second effect, knowledge externalities contribute to reducing future R&D productivity. The economic literature generally postulates that the first effect dominates the second so that knowledge externalities are generally positive, i.e., they have a positive impact on future R&D productivity (which corresponds to a positive value for $\epsilon$ in (**??**)).

The presence of knowledge externalities will create a gap between the level of investment in R&D chosen by firms and the socially optimal level. Indeed, when firms make their R&D investment decisions, they do not take into account the impact of current R&D on future R&D productivity (which will reduce or increase innovation costs for future innovators, depending on the sign of externalities). Hence, in case of positive (negative) knowledge externalities, a decentralized economy leads to underinvestment (overinvestment) in R&D compared to the optimal level because the level of private investment results from individual decisions that do not consider this external effect. Various instruments can correct the market failures generated by knowledge externalities. When they are positive, policy instruments should increase the profitability of private R&D so that firms become more inclined to invest in these activities. The implementation of subsidies that are proportional either to the cost of R&D or to the supply price of new knowledge is often proposed to correct such market failures (Grossman and Helpman 1991, Steger 2005). Likewise, when knowledge externalities are negative, it is necessary to levy taxes that are proportional to the cost of R&D or to supply price of new knowledge to reduce R&D profitability and limit incentives to invest in R&D.

## 2.2 The surplus appropriability problems: Consumer surplus appropriability and the deadweight loss effects of market power

The surplus appropriability problem results from the fact that it is impossible for firms to appropriate the entire potential increases in welfare generated by the commercialization of their innovations. Although the patent system creates an incentive to innovate by conferring monopolistic rents to inventors, it does not allow inventors to capture all the increases in welfare generated by their innovations. This is due to the type of authorized monopoly, which is not discriminant. Consequently, the classical monopolistic behavior of innovative firms creates distortions in prices and produced quantities compared to optimal levels and leads firms to underinvest in R&D. To illustrate our point, we graphically represent the static inefficiency linked to the imperfect appropriation of welfare (Figure 1) and illustrate the consequences in terms of dynamic inefficiency. The graph on Figure 1 represents the social welfare generated by the supply of a new differentiated good (an innovation). Let $D(P)$ be the demand function for the new good, $P^{MC}$ be the price defined by the monopoly firm and $P^{PC}$ be the marginal cost of production of the good (i.e., the market price in a competitive market). $Q^{MC}$ is the production of the monopoly firm while $Q^{PC}$ represents the production of the firm in pure and perfect competition.

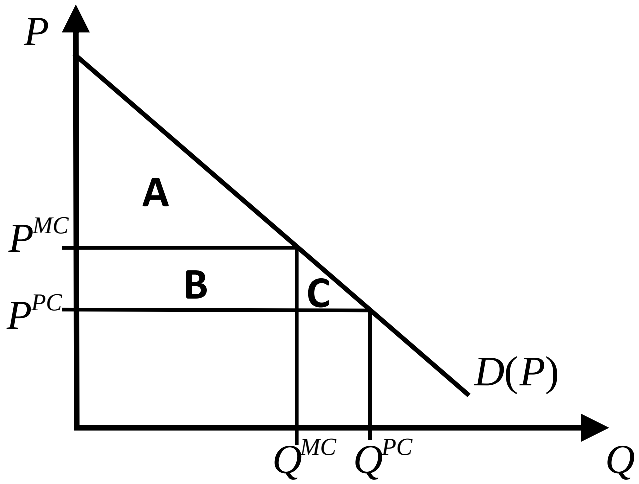


**Figure 1: The surplus appropriability problems**

At the decentralized equilibrium, the static welfare generated by the commercialization of a new differentiated good is represented by areas $A$ and $B$. Area $A$ measures the consumer surplus, i.e., the increase in welfare obtained by consumers whose reserve prices are higher than the selling price of the good. Area $B$ represents the firm profits, i.e., the difference between its total revenues and production costs. As we can see on the graph, the firm's monopolistic behavior induces a static inefficiency, measured by area $C$. By fixing the selling price above the marginal cost, the monopolistic firm restricts demand and consequently production compared to a situation in which the goods would be sold at their marginal cost (this is the famous deadweight loss effect).

In terms of dynamic inefficiency, the incentives to carry on R&D activities depend on the profitability of innovation, which is measured by the flow of profits obtained by firms in the intermediate sector following the market launch of a new product variety. The profit obtained at each period is represented by area $B$, whereas the potential increase in social welfare due to the launch of the new product is represented by area $ABC$. Thus, dynamic inefficiency does not only integrate static inefficiency (area $C$) but also takes into account the deficit in consumer surplus appropriation due to monopolistic behavior (area $A$). This deficit in the appropriation of the potential increase in welfare created by innovation is the source of the difference between the private and social returns to R&D. Consequently, this surplus appropriability problem constitutes a market failure that leads firms to underinvest in R&D compared to the optimal level.

Various public policies are likely to correct this type of failure. Using a variant of the model of Jones (1995b), Sorensen (2006) shows that the surplus appropriability failure caused by static and dynamic inefficiencies can be corrected by either a single instrument or by a mix of two instruments. The instrument capable of simultaneously correcting the static and dynamic inefficiencies consists of proposing a subsidy that partly covers the purchasing costs of differentiated goods. Such a subsidy would allow for increases in the demand for differentiated goods and the profits of the innovative firms, thereby augmenting the profitability of innovation and generating stronger incentives for firms to engage in R&D activities. Hence, such a subsidy allows for the correction of static (by increasing demand for differentiated goods) and dynamic (by increasing incentives to invest in R&D) inefficiencies. Sorensen (2006) also shows that this type of market failure can be corrected by a mix of two instruments. The first is a subsidy proportional to the production of differentiated goods and the second is a subsidy proportional to the cost of R&D. Subsiding the production of differentiated goods encourages firms in the intermediate sector to increase their production and thereby allows for the correction of static inefficiency (leading to the production of too few differentiated goods). However, such a subsidy does not contribute to increasing firm profits compared to the monopolistic situation because, although it encourages firms to produce more, it also causes them to reduce their prices to the marginal cost level. Hence, the profit obtained by firms is identical to the decentralized equilibrium profit. Using this instrument alone cannot incentivize firms to increase their investments in R&D; this is why it is necessary to combine this subsidy with another policy instrument capable of correcting dynamic inefficiency. A subsidy for R&D, which reduces R&D costs, can encourage more firms to engage in such activities. As a consequence, the global R&D investment level would be augmented and the dynamic inefficiency linked to the surplus appropriability problem would be corrected.

## 2.3 Duplication of R&D activities: The "stepping on toes" effect

Whereas the two types of market failure presented above lead firms to underinvest in R&D, other failures can have the opposite effect. Within an industrial sector, firms may engage in innovation races with the hope of being the first to file a patent for a new product or process. R&D programs may be set up concomitantly, which creates an important risk of duplication. From the perspective of social returns to R&D, such duplications constitute inefficiency. Indeed, when they make their investment decisions, firms do not account for the fact that part of their R&D activities will also be carried out by other firms. Thus, duplication externalities lead firms to overinvest in R&D compared to the socially optimal level. The existence of duplication is often used to support the hypothesis of decreasing returns to R&D: Doubling the resources engaged in R&D activities will not double innovation. In equation (5), $\lambda \in [0, 1[$ represents the degree of duplication externalities, i.e., the lower $\lambda$, the higher the duplication of R&D activities is.

To correct this failure, the theoretical literature proposes the same types of instruments as those used to correct the knowledge externalities failure. As shown by Steger (2005), a tax (or negative subsidy) based on the costs of R&D or the production of new knowledge can correct the duplication problem. Indeed, such taxes will reduce incentives to invest in R&D. Hence, regardless of whether duplications are caused by intentional behavior due to innovation races or accidental processes, taxes will increase the cost of R&D for firms and thereby limit global R&D investment. In addition, it should be noted that the microeconomic literature often proposes R&D cooperation as a way to reduce or even eliminate duplication problems (Dalhlia et al. 2004). It is also specified that the most integrative forms of cooperation are generally the most efficient in eliminating duplication problems. In particular, the creation of Research Joint Ventures (RJV), in which firms cooperate all along the innovation production process (from R&D activities to production decisions), would provide the required incentives to correct this failure.

## 2.4 The rent transfer problem: The "business stealing" effect

The transfer of rents from past to new innovators constitutes another failure that leads firms to overinvest in R&D. The most radical case can be found in quality-based growth models such as that of Aghion and Howitt (1992). Indeed, in this conception of growth dynamics, innovation renders existing products and technologies obsolete such that each new wave of innovation leads to the total transfer of rents from past to new innovators. In variety-based models, the transfer of rent is less radical. The launch of a new product variety by a firm reduces the demand for all the other firms producing differentiated goods and consequently reduces their profits, but it does not completely annihilate them.

The market failure caused by this rent transfer results in the tendency for firms to overinvest in R&D because they do not account for the negative effect of the commercialization of their innovation on the profitability of incumbent firms. Thus, at a decentralized equilibrium, the incentive to invest in R&D is too high and the pace of innovation is too rapid. The primary authors of the new growth theories (Grossman and Helpman 1991, Aghion and Howitt 1992) clearly associate this rent transfer with the famous creative destruction phenomenon described by Schumpeter. Following Grossman and Helpman (1991, chp.3,p.82-83), we should note that the use of a CES production function within variety-based growth models implies complete compensation between the marginal effect of an innovation on the consumer surplus (Area $A$ on Figure 1) and its effects on the reduction of incumbent firm profitability. Such a rent transfer will thereby limit the tendency to underinvest in R&D due to surplus appropriability problems. More precisely, this means that within variety-based growth models, the dynamic inefficiency caused by surplus appropriability problems is only linked to its static inefficiency (Area $C$), i.e., its monopolistic behavior. In contrast, this compensation is not automatic within the framework of quality-based growth models (Grossman and Helpman, 1991, chp.4, p.110-111). Indeed, because the rent transfer is total (and therefore more important), there is no automatic compensation between the welfare gains of consumers and the lost profits of incumbent firms.

As noted by Steger (2005), the instruments capable of correcting this failure are the same as those used to correct duplication problems, namely the implementation of a tax proportional to the cost of R&D or the selling price of knowledge. Such taxes will allow for reductions in returns to innovation and consequently the investment in R&D. The economy will grow at a lower rate and innovators will benefit from higher monopolistic rents over time.

## 2.5 Location externalities: Both sides of proximity effects

New Economic Geography and Growth models, which synthesize economic geography models with variety-based growth models, offer an interesting framework to account for interactions between the geography of economic activities and growth dynamics. Within these models, a new potential market failure appears to be linked to the economic geography. This market failure is the result of externalities generated by the chosen locations of firms (and consequently the locations of knowledge), which influence incentives to engage in R&D activities. Indeed, the assumption of (partially) localized knowledge spillovers implies that the marginal cost of knowledge production decreases with the spatial concentration of economic activities. Thus, in these models, the economic geography directly influences incentives to engage in R&D by changing the costs of such activities. In models with a NEG framework, the location choices of firms are only based on comparisons of the profits that they can obtain in each potential location. Consequently, firms do not consider the potential welfare effects of their choices. More precisely, in these models, the location choices of firms generate two main externalities that influence the level of investment in R&D in the economy.

The first externality generated by the location decisions of firms refers to the impact of the economic geography on (1) the value of assets and (2) the CES price indices of differentiated goods. Due to perfect competition in the R&D sector, the value of knowledge is given by its marginal cost of production. As in those models, the higher the spatial concentration, the lower the marginal production cost of knowledge is (due to higher spillovers), the nominal income of the owner of knowledge therefore decreases with the level of spatial concentration. Consequently, the economic geography that maximizes the nominal wealth of the knowledge owner is a dispersed equilibrium. Similarly, the location choices of firms also influence the proportion of transaction costs supported by each location. The NEGG literature (Martin and Ottaviano 1999, Montmartin 2013) shows that the economic geography that minimizes global transaction costs[7] is again a dispersed economic geography. Consequently, from the perspective of this externality (which includes two effects), when the economic geography is not perfectly dispersed (which is always the case when $A_i(0) \neq A_j(0)$), then the equilibrium location is not optimal because there is too much concentration. As a higher concentration implies a lower marginal cost of R&D, it follows that this externality leads agents to overinvest in R&D because they benefit from R&D costs that are lower than the optimal level.

The second externality generated by the location decisions of firms refers to the impact of the economic geography on the growth rate. As seen in (11), a higher concentration of economic activities reduces the cost of R&D, thereby increasing incentives to invest in R&D as well as aggregate growth. Thus, the aggregate growth rate is maximized when the cost of R&D is the lowest, that is, when activities are entirely concentrated in one location. From the perspective of this externality, when the economic geography is not completely concentrated in one country, the equilibrium location is not optimal because there is too much dispersion. As a higher dispersion of firms implies a higher R&D cost, it follows that this externality leads agents to underinvest in R&D because they suffer from R&D costs that are higher than the optimal level.

To summarize, the location choices of firms generate two main externalities that provide private firms with opposing incentives to invest in R&D. Consequently, the market failure generated by the location choices of firms seems to be ambiguous. Given the complexity of such models, we cannot analytically determine the optimal economic geography and know whether location externalities lead the market to over- or under-invest in R&D. We can, however, distinguish between two scenarios. If the concentration of firms in the market outcome is higher than the concentration in the optimal outcome, then externalities related to location choices generate a market failure that leads to overinvestment in R&D. In contrast, if the concentration of firms in the market outcome is lower than the concentration in the optimal outcome, then externalities related to location choices generate a market failure that leads to underinvestment in R&D.

The literature shows that the main instruments that are able to correct this market failure are location subsidies or taxes. Indeed, such instruments influence the relative profitability of each location for private firms. Consequently, firms will respond to these incentives, which modify the relative attractiveness of each potential location. Obviously, the appropriate policy depends on the sign of the gap between the concentrations of firms in the market and optimal outcomes. If this gap is positive (the market concentration is higher than the optimal concentration) then the appropriate policy will be to tax the core location, which hosts the majority of firms, or subsidize the peripheral location, which hosts fewer firms. The opposite policy should be implemented if the gap between the concentration of firms in the market and optimal outcomes is negative.

# 3 Too little or too much private R&D: How can we measure the gap between the social and private returns to R&D

In the previous section, we showed that different types of market failures may create a gap between the amount of R&D investment resulting from the decentralized equilibrium and its optimal level; some failures lead firms to underinvest in R&D whereas others lead them to overinvest. Theoretically, models generally fail to determine the overall result in terms of under- or over-investment. Answers have also been sought empirically. Indeed, different methods have been implemented to employ data to measure the real gap between the private and social returns to R&D and thereby infer any insufficiencies or excesses in private investment in R&D. This section is dedicated to presenting these methodologies and the obtained results to discuss the reality (and, if demonstrated, the magnitude) of the gap between the social and private returns to R&D. A summary of the present section can be found in Table 3 at the end of the paper.

## 3.1 The limitations of econometric estimates

Using a growth-accounting approach, the productivity literature proposes an econometrical measure of the impact of R&D activities on growth. This approach essentially connects the growth of total factor productivity (TFP) to R&D[8]. R&D investment is treated similarly to other capital investments within a classical production function. According to the following specification, the social return to R&D is defined by the partial derivative of production with respect to the R&D stock:

$$\triangle log A_t = \delta + \tilde{r}_{PL} \frac{R_t}{Y_t} + u_t \tag{12}$$

where $A$ represents the TFP, $R$ measures the level of resources devoted to R&D and $Y$ is the GDP. Parameters $\delta$ and $u$ represent the constant and the error term of the model, respectively. In this specification, we regress the TFP growth on the R&D share of output so that $\tilde{r}_{PL}$ measures the contribution of the R&D investment to the TFP growth, that is, the rate of return to R&D.

In this literature, private return to R&D are usually estimated empirically using the share of total turnover devoted to R&D at the firm level, whereas the measurement of the social return uses the intensity of R&D expenditures at the sectoral level to identify knowledge externalities between firms. This measure of the social return to R&D expanded rapidly and was greatly developed by Scherer (1982) and Griliches and Lichtenberg (1984), among others. Beyond the sectoral social return to R&D (i.e., private return plus intrasectoral knowledge externalities), the objective is to estimate the "imported" return (which refers to the impact of R&D activities carried out in other sectors on the productivity of the sector under consideration). The measurement of this "second component" of the social return to R&D requires the inclusion of a new variable within the production function: a measure of the R&D expenditures of other sectors. Weighting the role of each sector is generally performed using technological flow matrices among industries based on patent data or input-output exchanges.

According to this methodology, estimations generate two main results. On the one hand, the social return to R&D appears to be much higher than the private return, which would lead firms to significantly underinvest in R&D. On the other hand, knowledge externalities play a prominent role in this gap (see Griliches (1992) and Jones and Williams (1998) for a review). Therefore, Griliches concluded his survey of this literature (Griliches, 1992, p.43) as follows: "[...] there has been a significant number of reasonably well done studies all pointing in the same direction: R&D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates."

As also stated by Griliches (1992, p.44), however, the estimations provided in this field may overestimate the impact of knowledge externalities due to important measurement problems[9]. These are partly related to the fuzziness of the very notion of knowledge externalities, whose definitions and perimeters vary from one author to another. According to Griliches (1992, p.36), for instance, pecuniary externalities relative to the use of innovative inputs coming from other industries should not be regarded as knowledge externalities for firms, although they may generate important increases in productivity. Because they result from the difficulty of correctly evaluating the real value of purchased innovative inputs and are mediated through prices[10], they are not directly linked to the free use of new knowledge produced by external R&D activities. Consequently, they should be clearly distinguished from knowledge externalities. Such a distinction between knowledge externalities and other pecuniary externalities of innovation is, however, difficult to implement empirically. Therefore, estimations made in the productivity literature are likely to recognize pecuniary externalities of innovation as knowledge externalities, which may lead to an upward bias in explaining the gap between the private and social returns to R&D through knowledge externalities.

In addition, these measurement issues are also aggravated by the omission of numerous possible distortions associated with R&D in empirical studies. Jones and Williams (1998, p.1120) note, therefore, that, "In fact, theory provides some reason to question findings of the empirical productivity literature. The results of this literature are nearly based on a neoclassical theory of growth [...] that ignores many of the distortions associated with research that are formalized by new growth theory [...]. Because these considerations are omitted in the empirical literature, we may in fact have very little information about the true social rate of return to R&D."

The lack of modeling distortions such as those caused by appropriability problems, duplication or rent transfers within empirical studies, may have two types of consequences. First, it leads to the inclusion of phenomena that cause different types of distortions under the single umbrella term of "knowledge externalities", subsequently confounding the implications relevant for public policies. Indeed, it should be noted that when comparing the difference between the returns to R&D at the individual and macro-economic levels, the econometric literature on productivity effectively measures the global effect not only of knowledge externalities but also of rent externality problems. However, it does not make it possible to distinguish between these different effects. Second, although the employed econometric specifications have steadily improved to better reveal the diversity of the channels through which knowledge externalities are transmitted, they still largely neglect the other sources of market failures formalized by endogenous growth models (particularly those that lead firms to overinvest in R&D).

Recent reviews of the latest econometric studies that measure returns to R&D by Sena (2004) and Hall et al. (2010) present detailed examinations of the empirical studies that trace spillovers via connections between firms, industries, and countries. Also notable is the important strand of empirical literature relying on the theoretical intersection between the New Economic Geography and Economics of Innovation that proliferated during the 90s and 2000s and whose ambition was to measure the geographical dimension of knowledge externalities and estimate their impact on agglomeration forces and social return to R&D (for a review, see Rosenthal and Strange (2004) and Autant-Bernard et al. (2011, 2013)). However, although Hall et al. (2010) and Eberhart et al. (2013) note the enormous progress that has been made in econometric techniques to address the estimation problems revealed by the first round of productivity estimates, they also show that much remains to be done to robustly estimate the private and social returns to R&D and the difference between them[11]. Moreover, the rather clear conclusion that still emerges from this empirical literature, that private return to R&D is higher than to ordinary capital and that social return is even higher than private return, remains exclusively based on R&D spillover issues and continues to ignore other sources of differences between the private and social returns to R&D activities revealed by the theoretical literature.

As a result, we find the conclusion of Jones and Williams (1998) that the econometric literature on productivity fails to satisfactorily estimate the social return to R&D and contributes to the overestimation of the specific role of knowledge externalities to remain largely valid. However, considering the great variability in the obtained results, depending on the sectors or countries considered and the various possible biases revealed by the methodological reviews, it is unclear whether this leads to an upward or downward bias in measuring the gap between private and social returns to R&D. Given these limitations, many authors call for the reinforcement of the conceptual framework on which the empirical estimations are based. Hence, the approach proposed by Jones and Williams (1998) is worth presenting. Using a semi-endogenous growth model such as that of Jones (1995b), which allows for the diverse failures of a decentralized economy to be accounted for, points the way towards more theoretically based measurement strategies.

## 3.2 The advantage of theory-based measurement methods: Taking the diverse sources of market failures into account

Jones and Williams (1998) chose to theoretically define the social return to R&D as the total gain in consumption at time $t+1$ resulting from the reallocation of one unit of consumption towards R&D activities at period $t$, assuming that the knowledge stock remains unchanged at $t+2$. When applied to a variety-based, semi-endogenous growth model, this definition allows first, for the distinct formalization of the different possible forms of market failures; second, for the analytical derivation of the relationship between the theory-based measure of the social return to R&D and the existing econometric estimates of this return; and third, the analytical provision of a measure of the gap between the actual and optimal levels of investment in R&D.

The production possibilities of the economy are rather similar to that of Jones' model (1995). The most important difference concerns the innovation production function because Jones and Williams add another potential externality related to R&D activities:

$$(1+\psi)\dot{A}_t = \delta(aL_t)^\lambda A_t^\epsilon \tag{13}$$

where all parameters and variables have the same significance as in (5). Remember that $\lambda$ and $\epsilon$ refer to duplication and knowledge externalities, respectively. The new parameter $\psi > 0$ was introduced by Jones and Williams to better take the creative destruction process into account in variety-growth models. Indeed, even though growth models based on variety already include a rent transfer process from former towards new inventors, this transfer is less important and radical than in quality-based models. This parameter basically refers to the concept of innovation clusters. Innovations generally do not occur in isolation, which means that firms have to adopt all the interrelated innovations contained in a cluster to benefit from innovation. In the model, the introduction of $\psi$ implies that some new intermediate goods represent only an upgrade in existing goods and are not real innovations. Consequently, from the social point of view, only $1/(1+\psi)$ new goods actually increase welfare. In contrast, from the innovator's point of view, all new goods provide monopolistic rents (regardless of whether they are really new or not) so the introduction of $\psi$ will generate a new market failure that leads firms to overinvest in R&D.

Because the literature on productivity does not include all the market failures formalized in their model, Jones and Williams cannot directly link the social returns to R&D, as estimated within this literature, to the parameters of their model. They show, however, that it is possible to linearly approximate this relationship as follows:

$$\tilde{r}_{JW} = \tilde{r}_{PL} + (1 - \lambda) g_Y \tag{14}$$

where $\tilde{r}_{JW}$ represents the social return to R&D measured by the model of Jones and Williams (1998), $\tilde{r}_{PL}$ is the social return to R&D provided by the productivity literature and $(1 - \lambda) g_Y$ represents all effects that empirical literature does not take into account. Note that $(1 - \lambda) g_Y$ is strictly positive because $\lambda \in [0, 1[$ and $g_Y > 0$ at the equilibrium.

Such a theoretical interpretation of the econometric estimations of the social return to R&D leads Jones and Williams to a rather surprising conclusion. While the model introduces new sources of market failure that lead to overinvestment, the results still show that the literature on productivity underestimates the social return to R&D (with a maximum bias equal to the production growth rate when there is no duplication in the R&D sector). Thus, the econometric estimations provided by the literature on productivity would correspond to the lower bounds of the true social return to R&D. The explanation given for this is as follows: econometric studies ignore two dynamic factors that determine the social return to R&D, namely intertemporal knowledge externalities[12] and the gains (or losses) in capital caused by the time-dependency of the value of knowledge.

The framework constructed by Jones and Williams also allows them to define the functional relationship between the global level of R&D investment and its social return and then to derive an analytical measure of the gap between equilibrium ($I$) and optimal investment ($I^*$):

$$\frac{I^*}{I} = \frac{\tilde{r}_{PL}}{\tilde{r}_p - (1 - \lambda) g_Y} \tag{15}$$

where $\tilde{r}_{PL}$ is the social return to R&D provided by the productivity literature and $\tilde{r}_p$ is the private return to R&D. To evaluate the magnitude of private underinvestment in R&D, Jones and Williams (1998, p.1129), rely, on the one hand, on the existing econometric estimation of the social return to R&D, which ranges from 30% on average to 100% when including impact transiting from other industries, and, on the other hand, an estimation of the private return to R&D that ranges from 7% to 14%, in accordance with the average real stock market return. This conservative estimate indicates that optimal investment in research is more than two to four times actual investment.

With this methodology, Jones and Williams are able to estimate the gap between private and social returns to R&D that clearly takes the diverse market failures contained in R&D-based growth models into account. However, although it accounts for the diversity of R&D-based market failures and produces a clear answer regarding the degree of private underinvestment in R&D, such a structural approach still relies on econometric estimations of returns to R&D. Hence, it is not free of the measurement errors found in this literature. As stated by Hall et al. (2010, p.1135), "there is no reason to expect estimates of the ex post returns to be particularly stable over time or across sectors or countries". Consequently, if these estimates can still be useful for making comparisons among various sectors or countries and can guide R&D-related policy-making, it is necessary "to keep in mind that the measurement process is not a search for a scientific constant." (Hall et al., 2010, p.1136). Moreover, the method proposes a global estimation and does not tell us anything about the relative impact of each market failure when this has important policy implications. Public policies must not only be justified, they must be adequately designed to provoke the expected effects and the greatest degree of responsiveness on the part of firms.

## 3.3 Calibrating theoretical models to measure the relative impact of different market failures

Returning to the theory to better distinguish among the different sources of market failures appears to be necessary. According to Temple (2003), however, it would be illusory to try to directly confront the predictions of theoretical endogenous growth models against data from that perspective. Focusing on the search for a balanced growth path, these models demand restrictive assumptions and "It is not clear that we should expect models with this property to be the best approximation to the data [...]" Temple (2003, p.507). In contrast, if, as suggested in section 2, we consider these models to be useful devices for the analysis of welfare effects, one interesting approach would be to calibrate theoretical models. "[...] it will be virtually impossible to test the long-run predictions of growth models against the data. [...] Given this difficulty, one approach would be to calibrate a variety of models, under a range of assumptions. In the unlikely event that knife-edge restrictions are met in the real world, and hence long-run growth is endogenous, a suitably parameterized semi-endogenous model could still provide a reasonably good approximation to actual welfare effects." (Temple, 2003, p.503).

The sensitivity analysis method developed by Stokey (1995) is still a reference for calibration exercises on theoretical growth models. The general idea of Stockey's method is to calibrate the most known parameters of the model with data from previous studies and historical data (such as the GDP growth rate) and then analyze the sensitivity of the results depending on a large range of values for the most unknown parameters which often correspond to the key parameters of interest in the models (level of duplications, knowledge externalities, markups, etc.). Thus, this method addresses the problem of great uncertainty about the true magnitude of the various external effects present in such models. In this pioneering work, Stockey (1995) investigates the gap between market and optimal R&D investment by calibrating (for the US) a generalized[13] first-generation variety growth model such as that of Grossman and Helpman (1991, chap.4). Thus, Stockey's model includes the first four market failures presented in section 2. Even if the author does not provide a specific measurement for the impact of each market failure, this paper provides some interesting results for our purposes. Stockey (1995) shows that when the innovation technology is linear with the R&D stock, it is unlikely that the equilibrium level of R&D will exceed the optimal level. This result means that the "business-stealing" effect described in section

2 seems unlikely to lead to excessive innovation by itself. On the contrary, it seems that a curvature in the R&D technology (which corresponds to the values of $\epsilon$ and $\lambda$ in (13)) has the most systematic and strongest influencing on whether the equilibrium displays too much or too little R&D relative to the optimal level. The level of substitutability between goods and hence the market power of firms can also strongly influence the gap. More generally, the results provided by Stockey (1995) tend to show (1) a greater number of cases in which the market exhibits too little R&D rather than too much and (2) a higher potential magnitude for underinvestment compared to that for overinvestment.

Following Stokey's (1995) seminal work, Jones and Williams (2000) investigate the same question while focusing on measuring the impact of each specific market failure. The model developed in this paper is very similar to that of Jones (1995), i.e., a one-sector semi-endogenous growth model exhibiting decreasing returns to R&D. The model again incorporates the first four market failures presented in section 2 and is calibrated according to micro- and macro-econometric data. With realistic parameter values, the R&D investment of firms resulting from the decentralized equilibrium is 50% to 200% lower than the socially desirable level when duplication is limited (less than 75%). Indeed, when duplicated R&D activities and interest rates are too high, the simulations show that a decentralized economy can exhibit overinvestment. To measure the contribution of each market failure, the authors simulate the level of R&D investment when alternatively internalizing each source of market failure (assuming that the three others are still effective). When considering that the share of duplicated R&D activities ranges from 0% to 75%, the simulations generate 4 main results:

- the internalization of knowledge externalities would increase the R&D investments of firms by 16 to 36%;
- the internalization of the surplus appropriability problems would increase the R&D investments of firms by 140% (regardless of the degree of duplication);
- the internalization of failures due to the creative destruction process (rent transfer and innovation clusters) would lead to a 24% reduction in the R&D investments of firms (regardless of the degree of duplication);
- the internalization of duplication failures would have a "one-for-one" impact, i.e., when 25% of R&D activities are duplicated, the internalization of the corresponding failure would reduce the R&D investment of firms by the same proportion.

These simulations show that the impact of the surplus appropriability failure is generally prominent. More precisely, they clearly designate this failure as the main explanation for the pronounced underinvestment of firms in R&D. Indeed, once it is internalized, the model cannot conclude that there are situations of underinvestment and becomes highly sensitive to the chosen parameter values. This result seems to significantly contradict those usually presented by the literature on productivity, which places knowledge externalities at the heart of the explanation of the gap between the private and social returns to R&D. This difference, however, is more a matter of language than fact. As underlined by Griliches (1992, p.36), the literature on productivity recognizes pecuniary externalities of innovation as knowledge externalities. Now, as explained above, these externalities cannot be theoretically assimilated with knowledge externalities. They result from the imperfect market valuations of innovative inputs and not from the free unintentional diffusion of the knowledge necessary to produce them. Similarly, the proximity between the notion of pecuniary externalities and the surplus appropriability problems described in section 2.2 can easily be noted. Indeed, whereas the latter refer to informational and pricing constraints, which prevent innovative firms from capturing the entire increases in welfare generated by the market launch of their innovations, the former, describing the imperfect market valuation of innovative products and services, clearly reveals that part of the surplus generated by innovation benefits users and not innovators. Consequently, by at least partially integrating pecuniary externalities of innovation within the measure of knowledge externalities, the productivity literature undeniably confounds the impact of the two different sources of market failure, knowledge externalities and surplus appropriability, under the same measure. Therefore, when the econometric studies on productivity state that knowledge externalities are the main explanation for the difference between the private and social returns to R&D, this is much more indicative of an incorrect interpretation than a real contrast with the results of Jones and Williams (2000). This capacity of the employed methodology to distinguish between the two types of failure is what authorizes Jones and Williams to attribute the main part of the gap between private and social returns to R&D to surplus appropriability problems.

Concerning the importance of location externalities, the theoretical literature does not provide much insight. Indeed, the complexity of this class of models does not allow for the analytical determination of (1) the optimal location and, hence, (2) the social planner solution. Nevertheless, the welfare analysis carried out by Montmartin (2013), in which a NEGG model was calibrated, raises some interesting elements. Due to linear R&D technology, the simulations show that in most of cases, an increase in the market level of R&D investment increases welfare, indicating the existence of underinvestment in R&D. Nevertheless, the key result of the paper is to show that when knowledge externalities are strongly geographically localized (i.e., when the economic geography is more important for growth), an R&D subsidy policy generates opposite effects on the welfare of each location. This suggests that location externalities may have a strong influence on the deviation between the market and optimal economic geography.

Overall, although the different strands of the literature emphasize the existence and magnitude of a positive gap between the social and private returns to R&D, they do not attribute the causes of this to the same factors (knowledge externalities for some and surplus appropriability for others). This difference is especially important for public action because these two types of market failure require different instruments to be corrected (see section 2.2 and 2.3). Hence, the capacity to better account for the inherent characteristics of R&D activities explains the attractiveness of the theory-based simulation method developed by Stockey (1995) for subsequent contributions to research in this field.

## 3.4 Toward the idea of a smaller gap between market and optimal R&D: Recent contributions and refinements

In general, the main results provided by the economic literature until the early 2000s are conclusive on the existence of a significant gap between actual investment in R&D and what would be the optimal amount[14]. More recent contributions to this debate based on calibration methods, however, bring forth new elements that tend to call this central result into question.

Comin (2004) proposes a new method for measuring the contribution of R&D investment to TFP growth. Based on the free entry in R&D condition commonly used in growth models, this method offers the main advantage of not imposing a specific form on the dynamics of knowledge creation. The author uses data on R&D expenditure in the US to calibrate the parameters of his model[15] and obtains results that are markedly different from those proposed both by Jones and Williams (2000) and econometrical studies on productivity. Indeed, the contribution of R&D to productivity growth appears to be rather weak because it would only explain approximately 10% of average annual TFP growth[16]. For the author, two factors could explain this weak contribution. The first concerns the low observed intensity of R&D expenditures (approximately 2% of US GDP) in the long run, which would imply weak intertemporal knowledge externalities. The reasoning behind this is that if knowledge externalities were strong, a weak intensity of R&D expenditures at time $t$ would generate a high growth rate and substantially reduce the innovation costs of production at time $t+1$. Economic agents would be encouraged to increase their investments in R&D at $t+1$, which would be incoherent with the observed stability of the intensity of R&D expenditures. The second factor is that the low intensity of R&D expenditures leads to a limited knowledge growth rate, thereby reducing the potential impact of R&D on productivity growth (compared to other sources of productivity growth, such as human capital). It should also be noted that the chosen model for innovation embodied in new intermediate goods limits the size of externalities and thereby bounds the R&D contribution to productivity.

To propose a measure of the gap between the equilibrium and socially optimal levels of investment in R&D, the author specifies an R&D production function to obtain an analytical expression of the optimum. The calibration of this function according to US data shows that the optimal and observed investment levels are very similar. This result appears to be robust to significant variations in parameters. Therefore, according to Comin (2004), firms sufficiently invest in R&D activities because the global amount of private investment is close to the optimal level. As specified by the author, this result, which markedly differs from the existing literature, is linked to the chosen modeling strategy. The approaches developed by Alvarez-Pelaez and Groth (2005), Reis and Sequiera (2007) and Strulik (2007) also raise elements which question the magnitude of the underinvestment in private R&D as presented by Jones and Williams (2000).

Alvarez-Pelaez and Groth (2005) proceed from the recognition that, in variety-based growth models, firm market power, the share of differentiated goods within final production and the return to specialization are rigidly and arbitrary linked. Their objective is to investigate private underinvestment in R&D by developing a semi-endogenous growth model that does not directly link these elements. They first show that relaxing these restrictive relationships between parameters allows for more potential situations of overinvestment than is suggested by the variety-based models, such as that of Jones and Williams (2000). Then, applying the empirically estimated US values for markup, the share of capital within GDP and return to R&D, they demonstrate that although the existence of private underinvestment in R&D is a realistic hypothesis for the US, its magnitude is far lower than that suggested by previous studies.

Similarly, Reis and Sequieira (2007) develop a synthesis model à la Arnold (1988) that incorporates both an endogenous growth process à la Romer (1990), and a human capital accumulation process, à la Lucas (1988). In addition to relaxing the relationship between market power and return to specialization, they include negative externalities for human capital accumulation. In doing so, the authors intend to account for the "erosion effect" described by Galor and Moav (2002, p. 1148): "the time required for learning the new technology diminishes with the level of education and increases with the rate of technological change". This was also empirically confirmed by Kumar (2003) and Tamura (2006). According to this model, a decentralized economy is marked by three failures. The first two, which relate to knowledge externalities and firm market power (the surplus appropriability problems), lead private agents to underinvest in R&D, whereas the introduction of the "erosion effect" creates a new failure that encourages firms to overinvest in R&D. Indeed, at the individual level, researchers do not account for the negative impact of their activities on human capital accumulation, which can be seen as an effect of creative destruction. Because the emergence of a gap between equilibrium and optimal investment in R&D depends on the relative strength of these three effects, the authors calibrate their model using the results of empirical studies. This allows us to define a threshold value for the "erosion" parameter, from which the economy overinvests in R&D compared to the level that would be socially optimal. Comparing this value to that provided by the estimations of Kumar (2003) shows that situations of overinvestment are as plausible as situations of underinvestment. When the returns to specialization are very high, however, a decentralized economy clearly underinvests in R&D.

By developing an augmented two-R&D-sector model, à la Young (1998), with human capital accumulation and imperfect altruism, Strulik (2007) proposes an even more radical reassessment of the deviation of market R&D investment from the socially optimal level. Indeed, the existence of two interdependent R&D sectors that generate different degrees of externalities will moderate the influence of market failures on the equilibrium R&D investment level due to substitution effects between R&D sectors. Assume, for instance, an increase in the externalities generated by the variety R&D sector. In this case, a social planner would allocate more resources to this R&D sector than the market would but could simultaneously allocate fewer resources to the quality R&D sector, implying a potentially small impact on the overall R&D investment. However, the presence of capital accumulation and imperfect altruism in the model also mitigates the influence of market failures on the market level of R&D investment. Indeed, this allows for the appearance of channels through which population growth negatively affects growth and reduces the role of R&D externalities because growth in per-capita income is no longer driven solely by the TFP but also by growth in labor quality. The numerical experiments conducted by Strulik (2007) with US data show that the market share of employment in R&D is much closer to the socially optimal level than suggested by earlier numerical studies (especially that of Jones and Williams, 2000). More precisely, the ratio between optimal and market R&D is estimated as being between 0.91 and 1.03, suggesting very small potential deviations of the overall market R&D investment level from its optimal level. In contrast, Strulik's results highlight large sectoral misallocations of factors between R&D sectors. As noted by Strulik (2007, p.384), this shows that "the analysis has also shown that small deviation of the economy-wide R&D effort from the social optimum is compatible with relatively large sectoral deviations. Hence, the conclusion that laissez-faire provides approximately the optimal resource allocation does not necessarily follow. Due to specific sectoral externalities, a social planner might allocate researchers to sectors quite differently than the market, even though he chooses almost the same overall employment in research".

The works we have presented in this section, while never excluding the possibility that a decentralized economy could lead to underinvestment in R&D, strongly challenge the previous consensus regarding the presence of an important gap between private and social returns to R&D. Based on various refinements in the modeling of R&D within endogenous growth, these new developments highlight new sources of market failures (particularly in relation to human capital accumulation) and allow for a better understanding of this complex problem related to the allocation of resources to R&D in a way that does not merely answer the question of whether there is too much or too little R&D with "yes" or "no". Perhaps the main message of this work for R&D public policies could be the following: It increasingly appears that the main challenge that policy makers are now facing concerning R&D policies is not to increase the global amount of incentives for R&D but rather to try to efficiently allocate various instruments and funds across industries, regions and types of research.

## Conclusion

Many policy makers and economists who study R&D have long believed that market failures create a gap between the social and private returns to R&D, thereby limiting private incentives to invest in R&D. Thus, government intervention would be necessary to correct such failures and improve social welfare. Based on these arguments, many governments have implemented policies aimed at stimulating private sector R&D investment since the 80s.

However, this common belief in the widespread and significant underinvestment in R&D by firms compared to the socially optimal level of investment is increasingly being challenged. In particular, political, theoretical and empirical considerations have emerged that raise new questions regarding the rationale behind and efficacy of public policies designed to stimulate private R&D investment. The main questions are whether the market failures that cause insufficient private R&D investment really exist and whether massive, global public policy support for private investment in R&D is always justified.

In this paper, we have sought to clarify the answers to these questions provided, on the one hand, in the theoretical literature on endogenous growth theory and its integration with economic geography, and, on the other hand, in the empirical literature seeking to measure the social return to R&D in relation to its private return. In general, whereas the existing literature often considers only one type of market failure or confounds different types, creating imprecise analyses, we have clearly distinguished among different types of market failures and described their differing effects (positive or negative) on the gap between private and social returns to R&D. This has enabled us to clarify their differing policy implications.

Two main conclusions with non-negligible policy implications arise from this analysis:

1. Contrary to widespread belief, recent developments in both the theoretical and empirical literature on R&D-based endogenous growth do not support the existence of systematic underinvestment in R&D by firms. Indeed, when we account for the separate effects of different sources of market failures and estimate their relative importance, we find that circumstances in which there is insufficient private investment in R&D are less numerous and of less importance than previously thought (due to the non-negligible role of certain types of market failures, such as duplication, creative destruction or location externalities, which cause overinvestment in R&D).

In terms of public policy, these results lead to the following question: is massive global public support for private investment in R&D justified? Indeed, it appears that public financial support for private R&D should not be automatically and systematically implemented. Careful analysis of the factors that influence private investment in R&D should be undertaken to better target public interventions and implement them only when and where the existence of an underinvestment problem is confirmed, i.e., when market failure is more strongly associated with underinvestment than with overinvestment in R&D. In particular, there is a need for a new policy mix that does not merely increase incentives to invest in R&D but rather concentrates on searching for the most efficient allocation of funds across industries, regions and types of research.

2. Even when situations of underinvestment are identified, new measures of the social return to R&D, attained through the calibration of theoretical models, provide new evidence regarding the relative importance of different types of market failures. In particular, contrary to econometric analyses based on the estimation of innovation production functions, in which knowledge externalities play a prominent role (even though their impact cannot be clearly isolated), this new work finds the problem of surplus appropriability to be the main explanation for firm under-investment in R&D.

In terms of public policy, the appropriate balance of different financial instruments designed to address underinvestment in R&D is the relevant issue. Indeed, current public policies are mainly supply-oriented, employing such measures as subsidies or fiscal incentives to stimulate private investment in R&D. However, the greater impact of the surplus appropriability distortion relative to positive knowledge externalities would require a different policy orientation, one that is more consumption- or demand-oriented, i.e., designed to encourage the purchase of innovations.

Finally, this paper also reveals some of the main shortcomings in the macroeconomic growth literature and suggests avenues for future research. In particular, we argue for the development of theoretical and empirical models that integrate types of market failure that have not yet been incorporated into the literature on growth, such as uncertainty and financing problems. Improvements in models, which combine endogenous growth and new economic geography, also seem necessary to improve our understanding of the effects of interactions between geography, innovation and growth on incentives to undertake R&D investments. In light of the recent development in R&D policies that incorporate a geographical dimension (for example, cluster policy), this is certainly an important topic for future research.

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## Notes

[1]Concerning R&D activities, the objectives of the Strategy Europe 2020 are those of the Lisbon Agenda (2000). See http://ec.europa.eu/europe2020/index_en.htm

[2]Nevertheless, we have to specify that in very specific cases, the conclusions of these two classes of models concerning the need to support R&D can be significantly different. These differences are caused by the modeling of the creative destruction process, the implications of which we will discuss in the next section.

[3]see Jones (1995b, p.766) for a discussion of this assumption.

[4]In contrast to Romer (1990) or Grossman and Helpman (1991, chap.3), the creation of new varieties does not depend on past knowledge, i.e., this type of R&D does not generate spillovers.

[5]These pecuniary externalities refer to all changes in supply and demand related to the economic decisions of agents. In contrast to technological externalities, they are monetized by market results.

[6]Note that we can easily use a semi-endogenous process, as in Jones (1995b), without any complexity; see Minitti and Parello (2011) for further details.

[7]In this case, we define global transaction costs as the sum of the price indices in both countries or regions.

[8]See Carlaw and Lipsey (2003) for a review of the various interpretations and misinterpretations of TFP as an instrument capable of driving public policies for growth. In particular, reviewing measurement problems, they show that regardless of the method used to measure TFP, this indicator cannot correctly identify the "supernormal profit" associated with technological change. They conclude, "that although TFP is easily calculated it is difficult to interpret. Only under a very specific set of ideal conditions does it measure the super normal benefits associated with technological change. It is, therefore, at best only an indicator of how much measured output growth an economy achieves relative to measured input growth. It is not very helpful to policy makers who wish to test the efficacy of their industrial policies." (ibid, p. 475). Within this paper, we do not provide any additional discussion about the concerns on measurement and interpretation related to TFP; rather, we focus our attention on specific issues regarding how the productivity literature has been used to measure the magnitude of the gap between the private and social returns to R&D.

[9]For an in-depth discussion on these measurement issues, see Griliches (1979) and Griliches (1992).

[10]Note that this type of externality, which we call a pecuniary innovation externality, can also display negative effects when innovative inputs are overvalued relative to the productivity gains they generate.

[11]See, in particular, the interesting paper of Eberhart et al. (2013) showing that the implementation of a Griliches-type production function assuming cross-sectional independence and investigating knowledge spillovers assuming a known, additively separable functional form for R&D and spillovers, is inadequate even when the analysis focuses on private returns to R&D. Taking these cross-sectional interdependencies into account would lower the estimated private return to R&D. The authors therefore conclude: "In our mind, the search for a more appropriate specification of the knowledge production function that accounts for the true nature of cross-sectional interdependencies and allows identification of private and social returns to R&D should be regarded as the main challenge for the investigation of returns to R&D in years to come" (Eberhart et al., 2013, p. 439 ). It can be noted that this statement echoes late developments in spatial econometric techniques that are capable of better accounting for these interdependencies when estimating knowledge production functions.

[12]Jones and Williams note that the relative stability of R&D expenditures over time still allows econometric studies to capture, at least implicitly, these intertemporal externalities.

[13]In the sense that the developed model uses a rather general class of preferences that allows for a variety of types of competition among intermediate firms and decreasing returns in the aggregate R&D technology.

[14]For thorough reviews, see Cameron (1998), Carlaw and Lipsey (2003) or Hall et al. (2010).

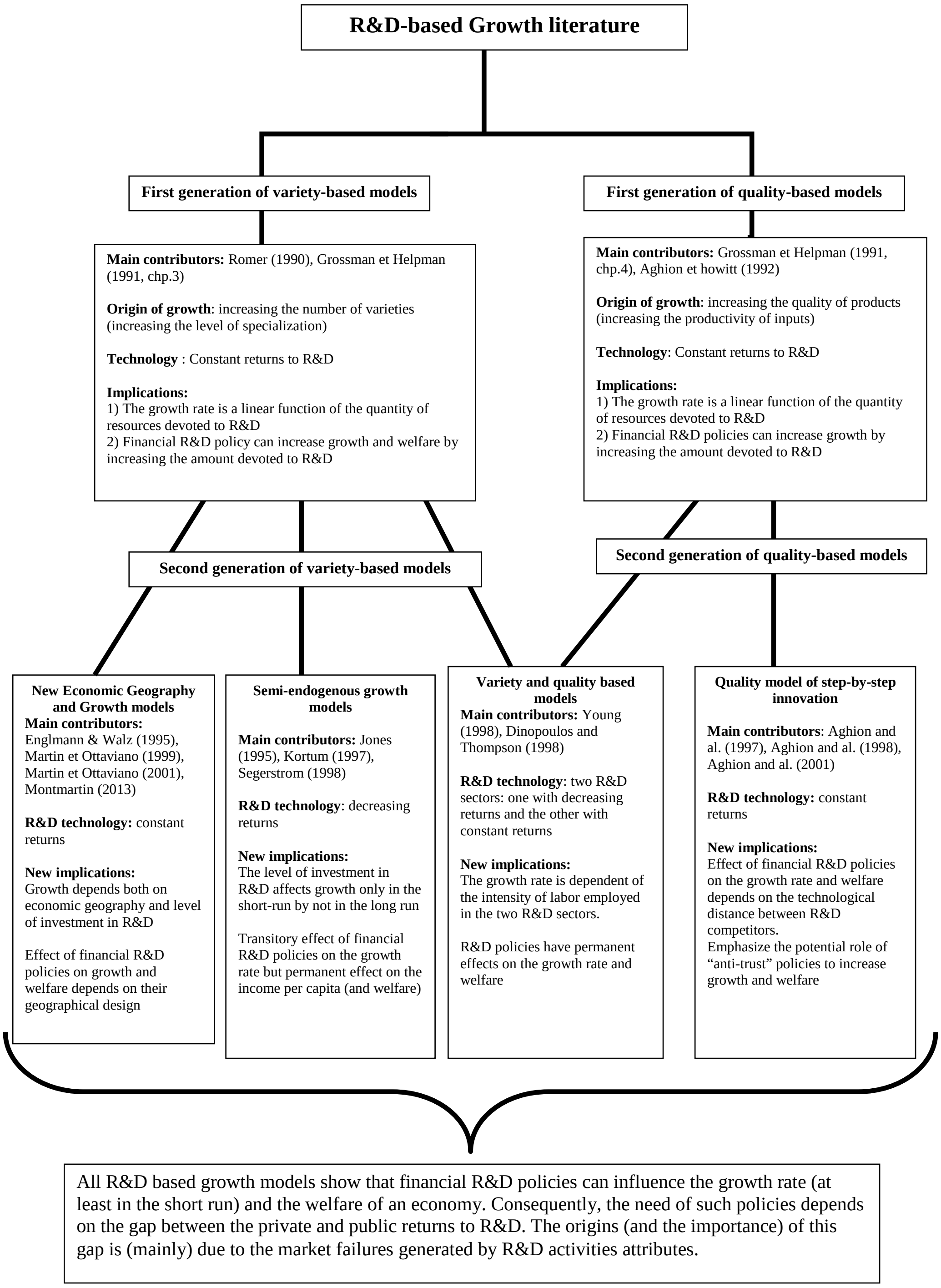
[15]Which is largely inspired by the model of Jones and Williams, although it does not specify any functional form for the knowledge production function.

[16]This result appears to be robust to great variations in the parameter values. When assuming an R&D intensity of 6% of GDP, R&D expenditures still cannot explain more than half of productivity growth. Moreover, the author extends his model by integrating problems of imitation and creative destruction and

by using diverse production functions for non-innovative goods. The obtained results all confirm the weak contribution of R&D expenditures to productivity growth.

# Tables

## Table 1: R&D, Innovation and Growth: Modeling and Public Policies



## Table 2: Main sources of market failures and instruments to correct them

| Market failures | Implications on incentives to invest in R&D | instruments |
|---|---|---|
| **Knowledge externalities** | | |
| *standing on shoulders > fishing in the same lake* | Under-investment | - Proportional Subsidies to R&D cost or patent<br>- Cooperation incentives can reduce the need of subsidies |
| *fishing in the same lake > standing on shoulders* | Over-investment | - Proportional Taxes on R&D cost or patent |
| **Surplus appropriability** | | |
| *Consumer surplus*<br>*Market power* | Underinvestment | 1) Proportional Subsidies to purchase cost of innovation<br>2) A mix of two instruments : proportional subsidy to the production of innovative goods + proportional subsidy to R&D cost |
| **Duplication** | | |
| *Stepping on toes* | Overinvestment | - Taxes on R&D cost or on patent<br>- Cooperation incentives can reduce the need of taxes |
| **Rent transfer** | | |
| *Business stealing effect* | Overinvestment | - Taxes on R&D cost or on patent |
| **Location externalities** | | |
| *Positive proximity externalities > negative proximity externalities* | Underinvestment | - Subsidy to the “core” location or tax to the “periphery” location (in order to increase spatial concentration) |
| *Negative proximity externalities > Positive proximity externalities* | Overinvestment | - Taxes  to the “core” location or subsidy to the “periphery” location (in order to reduce spatial concentration) |

## Table 3: Measuring the gap between private ad social return to R&D: methods and results

| | Econometric measures | Theoretical – based simulations |
|---|---|---|
| **Methods** | Estimation of production functions or cost/profit functions | Linking theoretical endogenous growth models to econometrical results on productivity measures |
| **References** | Numerous papers. Review by<br>Griliches (1992)<br>Cameron (1998 )<br>Jones and Williams (1998)<br>Hall, Mairesse, Mohnen (2009) | Few papers :<br>Jones and Williams (1998, 2000)<br>Comin (2004)<br>Alvarez-Pelaez and Groth (2005)<br>Reis and Sequeira (2007)<br>Strulik (2007) |
| **Market failures considered** | Knowledge externalities and surplus appropriability problems<br><br>But not distinguished | The four types : knowledge externalities, appropriability problems, duplication and rent transfer |
| **Main results** | R&D social return largely superior to R&D private return<br><br>Private return : 7 to 15 %<br>Social return: 30 to 100%<br><br>Inducing private underinvestment in R&D | Jones and Williams (1998, 2000): Underinvestment but essentially due to appropriability problems<br><br>Comin (2004): actual investment equal optimal investment<br><br>Alvarez-Pelaez and Groth (2005) ; Reis and Sequeira (2007); Strulik (2007): potential situations of overinvestment |

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