Department of Economics

R and D in R&D.

Endogenous Growth and Welfare

Daria Denti

Thesis submitted for assessment with a view to obtaining the degree of
Doctor of Economics of the European University Institute

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EUROPEAN UNIVERSITY INSTITUTE
Department of Economics

R and D in R&D: Endogenous Growth and Welfare

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Part I

Introduction

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I started this thesis with the objective and hope of understanding and contributing to research into the role of R&D in determining economic growth, by disentangling R&D components and focusing on their different effects on the economy.

Starting from path-breaking contributions in the 1990s (*i.a.* Romer 1990; Grossman and Helpman, 1991), much work has been done in the past decades to establish that R&D is a key driver of economic growth. Within this strand of literature, many authors have analyzed the linkages between R&D-based technological progress and several issues: from employment to international comparisons, from differences between R&D creation and imitation to different patterns of R&D adoption[1].

To the best of my knowledge, in all these works R&D is usually treated as a homogeneous activity, even tough there are some well-established results showing that the distinction between R&D components is relevant in economic terms. In some works, private R&D is distinguished from public R&D: private R&D is production oriented, whereas public R&D acts as a public good positively affecting private R&D through spillovers.

However, data show that other distinctions may be meaningful. Both in US and UK, it is acknowledged that private agents perform multi-stage R&D processes, where both development and basic research are carried on (NSF[2], 2004; SPRU[3], 1996). Furthermore, economic theory and empirical works have highlighted meaningful distinctions between basic research and development along a variety of dimensions (*i.a.* Nelson, 1959, Aghion and Howitt, 1999) and it has been pointed out that failing to distinguish between innovative activities may be

[1] see Gancia and Zilibotti for a review (Gancia and Zilibotti, 2003)
[2] US National Science Foundation
[3] Science Policy Research Unity, University of Sussex

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potentially misleading: "*whether growth will be enhanced by a subsidy to innovation might depends crucially on whether product or process innovations are subsidized, or on whether basic or applied research is encouraged by the subsidy*" (Aghion and Howitt, 1999).

These observations suggest that there may be scope for investigating the consequences on growth and welfare of distinguishing basic research (R) from development (D). In this thesis, I consider these peculiarities by introducing basic research in R&D-based models of endogenous growth along with development activity.

I started by presenting a detailed review of relevant evidence and literature focusing on the main differences between R&D activities and on their effects on the economy. In this way, I provide the background on which my further analysis will be based and I am able to show that questioning the relevance of distinguishing between research activities may be of some interest.

Given these premises, I have tried to develop a set up able to capture the relevant features distinguishing basic research from development and to embed them in an endogenous growth framework where innovation drives growth. The most important elements that have been introduced are: multi-stage research processes, differences in externality effects played by each components of the R&D, multi-industry set up where industries differ in term of R&D performed. While the former features constitute the core of thesis and are, therefore, introduced from the beginning, the latter appears in the third chapter, where I will develop a multi-industry set up to account also for inter-industry spillovers. Introducing these features has led to really interesting findings. Distinguishing among innovative activities is important

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both for growth and for optimal policy design: subsidizing R&D as a whole, as suggested by existing literature on horizontal innovation is not optimal in terms of welfare. Also the counter-factual scale effect, affecting the majority or horizontal innovation models disappears endogenously.

The economy analyzed in Chapter 2 is such that all firms perform multi-stage R&D, letting the focus being the consequences of accounting for R and D without any noise generated by cross-industry effects This model offers many insights to the debate about the role of R&D on growth:

1. the scale effects disappears endogenously without semi-endogenous growth;

2. productivity of basic research exercises two opposite effects on growth; overall they cancel out. The same happens with productivity of development;

3. an economy grows more if applied designs are generated through a technology relying relatively more on basic research than on other R&D inputs;

4. from a policy-making perspective, it turns out that: *(i)* from a welfare perspective, the optimal choice is supporting basic research only and that *(ii)* from a growth perspective, patronizing R&D in fields with a not-too-low probability of commercial exploitation is beneficial.

5. if we add learning-by-doing by scientists (basic research exerts a positive externality effect also on scientists transforming basic research ideas into final blueprint), we see that the main findings are emphasized.

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However, the framework developed in Chapter 2 neglects an important fact about R&D processes in the economy: depending on the industry considered, the patterns of R&D processes change dramatically. Theory and case studies suggest that industries relying on basic research are characterized by long term positive profits from breakthrough innovations, whereas industries preferring production-oriented short-goal innovation are subject to imitation and consequent erosion of monopoly profits. To account for these features, a multi-industry set up is necessary, where industries differ in term of R&D process performed. This set up allows also for inter-industry spillovers and can be rewritten to address international relationship and cross-borders R&D externalities issues. Obviously, two industries and many sectors, while providing a good level of fitness to the data, determine a heavy analytical treatment. Nonetheless, interesting outcomes arise:

1. R&D spillovers affect the economy in a different way, not only because we allow for inter-sector spillovers, but also because cross-industry relationships channel intra-sector externalities too;

2. R&D spillovers trajectories cause differences in the effects of some technological features on growth, such as productivity of R&D activities and probability of commercial exploitation of designs;

3. erosion of payoffs exerts a negative effect on the economy;

4. there is still absence of the scale effect;

5. R&D policy design shows important differences compared to the single-industry set

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up.

6. the introduction on an international setting with technological diffusion and imitation shows technological leaders won't lose their leadership even when followers stop copying thanks to basic research effects on final good productivity.

Finally, besides important contributions in literature on R&D acknowledging the positive and pervasive effect of basic research throughout the whole economy, there is an increasing stock of anecdotal evidence and case studies showing and discussing the accidental trajectories of fundamental knowledge generated in the industry towards environmental support. Indeed, there is enough evidence to claim that private R&D may affect pollution even accidentally, through basic research, and to set a framework able to analyze the consequences of this relationship on growth. This exercise proves to be useful under many perspectives. It helps showing that the introduction of multi-stage R&D process inside a growing economy allows to accomplish many tasks

1. it might be used to address various issues;

2. it provides a novel perspective to the debate on the relationship between environmental care and economic growth, by bridging the traditional vision which deals exclusively with R&D activity explicitly aimed at pollution-abatement, acknowledging also indirect and unintended effects;

3. it gives sound insights on the way policy should be designed: actions to support environmental preservation might be embedded inside actions to support production,

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which is a further step in favor of sustainable growth.

It is worth noticing that, in the economy analyzed in Chapter 4, environmental policy is enforced, through support to R&D devoted to production and not to R&D devoted to pollution-abatement.

In the next section I present a brief summary of each Chapter. Each of them is self-contained, which comes at the cost of partial redundancy given the highly overlapping nature of some parts.

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Abstracts of Thesis Chapters

Abstract of Chapter 1: A Review of Literature and Data on R&D

This Chapter provides a review of relevant works on R&D and its components. Both empirical and theoretical contributions are presented. Economic theory and empirical works highlight meaningful distinctions between basic research and development along a variety of dimensions. Data show that private agents perform multi-stage R&D processes, where both development and basic research are carried on. Literature and evidence disclose the main patterns of multi-stage R&D processes. Anecdotal evidence outlines that privately-performed basic research generates technological roadmaps able to influence heavily innovation patterns throughout many industries. These observations suggest that there may be scope for investigating the consequences on growth and welfare of distinguishing basic research from development inside private R&D activity.

Keywords: basic research, development, R&D policy.

Abstract of Chapter 2: Basic Research and the Scale Effect in a Growing Economy

Multi-stage research processes are introduced in an horizontal innovation economy where R&D is performed by private agents only. Basic research (R) is the first stage and its output is used to develop an applied design (D). Fundamental ideas have the highest level of generality and generate intra-industry spillovers. Development spillovers benefit development only. The counterfactual scale effect typical of many standard horizontal innovation models disappears endogenously. Productivity of any research step does not affect growth.

Technology in the R&D process influences growth: the more it relies on basic research, the more the economy grows. R&D policy to attain social optimum consists of basic research subsidies only, showing that if firms pursue multi-stage R&D, which activity has to be subsidized becomes crucial. Adding learning-by-doing by scientists working with basic research does not alter the main findings.

Keywords: endogenous growth, expanding variety, R&D, basic research

JEL Classification: D92, E62, O31, O38.

Abstract of Chapter 3: Multi-Stage Research Processes in a Multi-Industry Economy

In an economy with a development-intensive industry and a basic research-intensive one, basic research is the intermediate output of the research process in its own industry. Basic research production is not inspired by the needs of any producer of goods. Output of research activity relying on basic research does not always translate into a new product, but when it does, it generates perpetual monopolistic payoffs. Basic research plays inter-sector and intra-sector positive externality effects on productivity. Development activity delivers new products with certainty, but it is subject to erosion of monopolistic power. A stable and unique interior solution is found where the scale effect is ruled out. Erosion of monopoly power has two main consequences: reduces the growth rate by and creates market failure. Productivity of R&D in the development-intensive industry has a negative effect on growth. On the contrary, basic research productivity exerts overall a positive effect. Probability of economic exploitation of breakthrough innovation may have different effects on growth, depending on R&D technology characteristics. In general, if R&D does not rely heavily on basic research, then there is a threshold value for the probability of commecialization: if it is low (high), then it should be increased (reduced) to benefit growth. If R&D relies heavily on basic research, then an increase in commercial exploitation harms growth. The decentralized equilibrium is not Pareto optimal. Optimal fiscal tools concerning R&D are: support for basic-research-intensive industry and basic research in particular. Taxation of R&D in the industry neglecting basic research. Secrecy efforts enforced by firms determine taxation, showing that it is good for the economy to spread fundamental knowledge even when performed by private firms. The set up is useful to address the issue of imitation and international technological leadership. The main finding shows that, if technological leaders are such because they perform basic research, then basic research grants to leaders that they never turn to followers.

Keywords: endogenous growth, expanding variety, R&D, basic research.

JEL Classification: D92, E62, O31, O38.

Abstract of Chapter 4: Cleaning the World Doing Maths

Pollution is introduced in a horizontal innovation framework with multi-stage R&D process and research spillovers associated to each R&D component. Basic research benefits from feedback from applied knowledge. Firms do research to get a new variety of good granting positive payoffs. However, new varieties of goods feed pollution which, in turn, acts as a negative externality on workers. Within R&D, basic research, along with being the first necessary step for any R&D process, contributes to abate pollution unintentionally through its generality and pervasiveness. A unique growth rate is determined where each research activity has peculiar effects: development exerts both negative and positive influences. Decentralized equilibrium is not Pareto efficient. Fiscal policy supporting basic research by taxing polluters is second-best optimal as long as R&D performs little basic research. This finding shows that environmental care needs not necessarily to harm growth and that it can be pursued also by helping activities that contribute indirectly to abate pollution.

Keywords: basic research, spillovers, endogenous growth, pollution, second-best environmental policy

JEL Classification: H23, O30, Q58

Part II

Chapters

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CHAPTER 1

A REVIEW OF LITERATURE AND DATA ON R&D

> "*One major barrier to entry into new markets is the requirement to see the future with clarity. It has been said that to foretell the future, one has to invent it. To be able to invent the future is the dividend that basic research pays.*" -E. Wong. University of Science and Technology, Hong-Kong-

There is now a large and influential literature acknowledging the importance of R&D as an engine for growth (*i.a.* Romer, 1990; Gancia and Zilibotti, 2003; Barro and Sala-I-Martin, 2004). This literature does not address questions related to the effects of the different components of an R&D process on growth, even tough there are some well-established results showing that the distinction between R&D components is relevant in economic terms.

Data show that private agents perform multi-stage R&D processes, where both development and basic research are carried on (NSF[1], 2003). Literature on R&D management has widely assessed that R&D performed by firms in certain sectors is a multi stage-activity (*i.a.* Bodner and Rouse, 2005) which has also been modelled at the micro-level. Furthermore, economic theory and empirical works have highlighted meaningful distinctions between basic research and development along a variety of dimensions (*i.a.* Nelson, 1959; Funk, 2002). An

[1] National Science Foundation

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increasing amount of literature on innovation, technology and R&D management acknowledges the huge impact of basic research -also privately performed- in shaping the patterns of innovation and its returns (Auerswald and Branscomb, 2005)

These observations suggest that there may be scope for investigating the consequences on growth and welfare of distinguishing basic research (R) from development (D). In this paper, we review the relevant contributions, both theoretical and empirical, on which the theoretical frameworks developed in the following chapters will hinge.

We start providing the definition of each component following what has been established by the National Science Foundation of United States and subsequently adopted in the literature on R&D.

Basic research is defined as a "*systematic study directed towards greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific application towards procedures and products in mind*". Development is defined as "*a systematic application of knowledge towards the production of useful materials, devices, systems and methods, to meet specific requirements*" (Audrestch *et al.*, 2002; Eisenman *et al.,* 2002). The focus on basic research and development may appear to neglect the existence of another step, applied research, but in fact this is not the case, as applied research is embedded with characteristics of both basic research and development without any strong peculiarity.

The idea of distinguishing basic research from the other research activities when studying endogenous growth builds on the two broad arguments mentioned above. Here we explore these arguments on which our theoretical assumptions will be based.

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First, basic research appears to play a relevant role both in US data and Government's agenda. To this respect, we list several relevant facts:

- R&D activity in the US is carried on mainly at industry level and it is performed by private agents (NSF, 2003).

- Private agents perform basic research (NSF, 2003).

- Some industries perform more basic research than others (Auerswald *et al.*, 2005; Eisenman *et al.,* 2002).

Figure 1.1-1.3 highlight the patterns of firms investments in basic research and development in United States between 1953 and 2003[2]

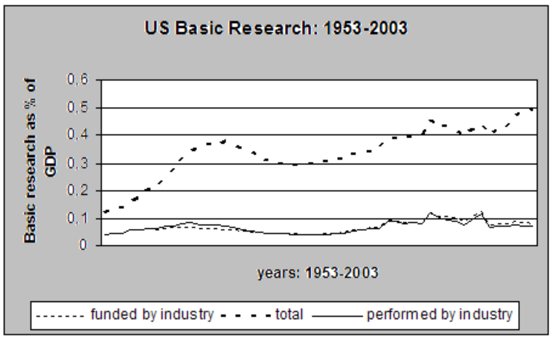

Figure 1.1. US Basic Research in Industry

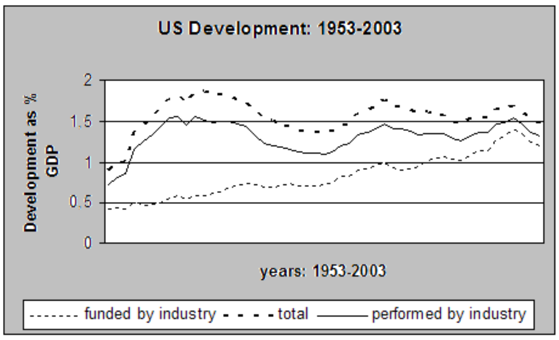

Figure 1.2. US Development in Industry

[2]Source: National Science Foundation (NSF). *National Patterns of Research and Development Resources: 2003.*
Data are in millions of constant 1996 dollars.

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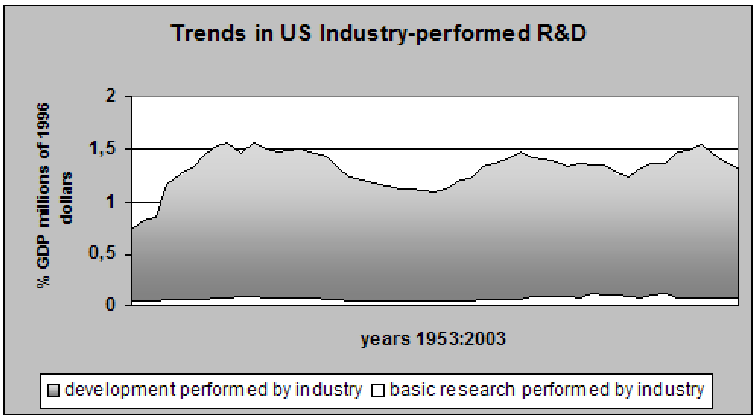

Figure 1.3. US Industry-Performed R&D

Starting in the 1960s and 1970s, industrial innovation in the US was identified with some corporate entities, which were pursuing far-sighted research. Recruitment of researchers was aimed at attracting the most able people, who were provided with a great deal of latitude in performing R&D. The most famous companies adopting this strategy were General Electric, IBM, Bell, Xerox, and their scientific achievements have been recognized by several Nobel prizes (Auerswald *et al.*, 2005). Nowadays, companies' support to the "blue-sky" research has changed, as the majority of firms tends to prefer investing in short-term R&D. However, it is important to notice that there are important exceptions: in some industries, such as electronics and chemistry, firms invest significant amount of money in fundamental research as they reckon this to be the most suitable strategy to long-term survival (Auerswald *et al.*, 2005); a key example is given by the Google R&D strategy encouraging engineers and scientists working in the company to spend a fraction of their working schedule on whatever research project strikes their fancy[3]. Some of Google's newer services and products have

[3]This strategy is called "Google 20 percent"

originated from these independent endeavour (Mayer, 2006).

Literature on R&D management and industrial engineering have widely recognized multi-stage R&D processes performed by firms: starting from seminal works where the relationship between the different R&D steps has been firstly formalized (Stokes, 1997), many contributions have followed testing the relevance of the linkages and further refining them.

Multi stage R&D has been identified along the following definition: "*R&D typically embodies a multi-stage process, whereby a line of R&D passes through stages such as basic research, exploratory development and applied development*" (Bodner and Rouse, 2005), which embeds two multi-stage R&D models: the linear paradigm and the dynamic paradigm (Stokes, 1997). Both perspectives have been designed to account for multi-stage R&D processes, the difference being that the former does not allow feedback from development to basic research, whereas the latter does. Summarizing, tough unkindly, the various contributions in this field, we can acquire a stylized process for multi-stage R&D, which we depict in Figure 1.4[4].

[4]For a detailed discussion and evaluation of multi-stage R&D processes and the derivation of a diagram like the one presented in Figure 1.4 see Bodner *et al.,* 2005 and Stokes, 1997. The number of stages within an R&D varies: in Figure 1.4 we represent a four-stage R&D process, the stages being: basic research, early-stage technology development, applied research, development (Auerswald and Branscomb, 2005)

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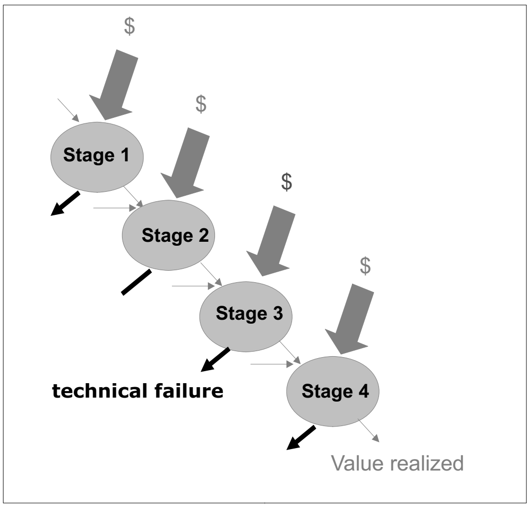

Figure 1.4. Multi-Stage R&D Process

Stage 1 corresponds to basic research and the following steps lead to development of the final design. Each stage requires investment by firms and it entails some degree of technical failure. The final design is obtained going throughout the whole line, therefore development is the necessary final stage after research (Bodner *et al.*, 2005). Is it noteworthy that this structure is not just speculative, as it has been tested to match firm actual organization of multi-stage R&D processes and it is used to simulate portfolio choice on R&D investments.

If we add spillovers to the picture, then the analysis becomes more complicated. As we have said above, there are two ways through which spillovers from R&D components may influence the multi-stage R&D process. The linear paradigm entails a unique direction for the flow of knowledge. from basic research to development with no feedback. So, only research externalities may affect the process by influencing development. The dynamic paradigm broadens the possible trajectories for knowledge, so that also feedbacks from development to basic research are allowed (Stokes, 1997). Case studies, historical and anecdotal evidence

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show that both ways operate (Stokes, 1997) In this thesis, we will tackle both paradigms: we will focus on the linear one in the following two chapters and we will switch to the dynamic paradigm in the last chapter.

Within endogenous growth literature on horizontal innovation, there are some attempts to deal with different R&D activities performed by firms. One of the key contributions disentangles two R&D activities -corporate R&D and entrepreneurial R&D- (Peretto, 2003, 1999a, 1999b) being the former performed along with production and the latter performed to develop a new design. Although the latter is necessary to have the former, it is just an entry condition: knowledge generated by entrepreneurial R&D is not used as input in corporate R&D. So, the patterns highlighted in Figure 1.4 are only partially fulfilled.

Economic literature has addressed questions about the economic effects of basic research starting from Nelson's seminal contribution "The Simple Economics of Basic Scientific Research" (Nelson, 1959) and further discussions and analysis by other authors (*i.a.* Link *et. al.,* 1981; Pavitt, 2001, Audretsch *et. al.,* 2002). These contributions have identified several distinguishing features which we briefly present.

- Basic research is the R&D activity whose output is the most likely to fail to be directly economically exploitable to produce new intermediate goods. "*Although risk is associated with all forms of R&D, uncertainty is an inherent characteristic of basic research. Not surprising that the outcome and the direction of basic research is often unpredictable*" (Link et. al., 1981); "*Moving from the applied research end of the spectrum to the basic research end, the degree of uncertainty about results of specific*

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research projects increases and the goals become less clearly defined and less closely linked to the solution of a specific object" (Nelson, 1959).

- The same elements implying that not all the designs developed by basic research efforts are economically exploitable, while the designs resulting from development efforts are more likely to be so, also entail that basic research is more likely to generate breakthrough innovations than development activity (Nelson, 1959; Theis and Horn 2003). Development refers to testing or improving existing goods, processes or prototypes: as a research activity, it is aimed towards improvement of something known rather than discovery of the unknown. Basic research, on the contrary, does not have any precise goods, process or prototype to work on. Its aim is mainly the exploration of the unknown. Obviously, new, breakthrough innovations are more likely to come out from new understanding of something that was previously unknown than from improvement and enhancement of what is already known. If we look at the literature on R&D, we see much emphasis devoted to the role of basic research in generating breakthrough innovations (Audretsch et al., 2002; Theis and Horn, 2003)[5].

- Even when a basic research design is economically exploitable, it usually needs further efforts to be suitable for the production of an intermediate good (Nelson, 1959; Auerswald *et. al.*, 2005).

[5]There are many examples of private firms declaring to invest in basic research for strategic reasons: Microsoft Corp., has made notable research investment in recent years, including hiring some excellent mathematical physicists; Intel Corp. is investing in a series of research labs located in close proximity to some top universities; IBM is investing in new materials, new architectures and algorithms. Bell Labs efforts in fundamental research on nonlinear optics, optical properties of rare earth ions and soliton dynamics have produced breakthrough innovations granting long term positive payoff for the company.

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- Literature on industrial economics has asserted that basic research generates positive and significant spillovers affecting the economy across sectors, whereas spillovers associated to development activity are generally weak and do not spur across different sectors (*i.a.* Lichtemberg and Siegel, 1991; Kesteloot and Veugelers, 1995; Funk, 2002).

One last comment refers to R&D policy. It is widely documented that basic research has been playing a key role in US political agenda since the 40s. To this respect, basic research is considered fundamental to get major achievements in many different fields, therefore, keeping US leading position as exporter of goods and services (PCAST[6], 2002; OSPT, 2003b; OMB[7], 2004) and it is acknowledged to be both necessary and sufficient for technical progress (Stokes, 1997; Pavitt, 2001). This political vision has actually determined the continuous flow of public funding for basic research both at academic and firm level that we see in US data. To this respect, we list several facts:

- US Government promotes public funding for R&D at industry level of R&D performance (PCAST, 2001; PCAST, 2002; OSTP[8], 2003a).
- Data on federal support to R&D in US shows that different fiscal incentives are used depending on R&D composition. In particular, federal support is mainly directed towards basic research activity and early-stage technological development (ATP[9], 2007). Pattern of public support to industrially performed basic research is depicted in Figure 1.5

[6]President's Council of Advisors on Science and Technology
[7]Office of Management and Budget.
[8]Office of Science and Technology Policy
[9]US NIST Advanced Technology Program.

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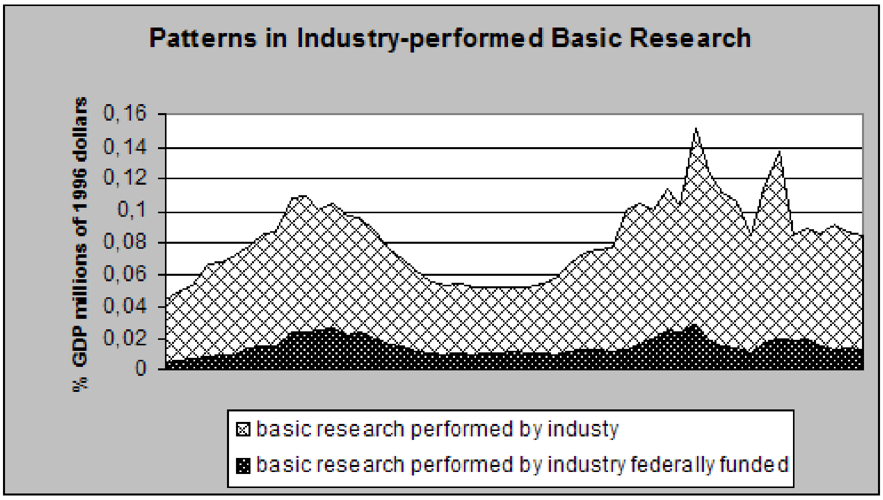

Figure 1.5. Patterns of Public Support to Industry-Performed Basic Research in US

- Federal support to private R&D is directed mainly to certain industry sectors which perform long-term basic research (NSF, 2003).
- Nowadays, there is an international debate on the adoption of similar policies in other countries (Trunmbull, 2004).

In standard R&D-based endogenous growth framework fiscal policy needed to reach the first best allocation is neutral with respect to R&D composition as R&D is treated as homogeneous in terms of its composition (Barro and Sala-I-Martin, 2004). Therefore, no fiscal instrument devoted specifically to privately performed basic research arises. However, the evidence on federal support to R&D in US shows that different fiscal incentives are used depending on R&D composition. In particular, federal support is mainly directed towards basic research activity and federal programs have been established to support firms in tackling fundamental research. Therefore, constructing a set up where basic research is

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disentangled from development and analyzing optimal fiscal policy enable to check whether the observed differences in fiscal incentives are good in terms of welfare or if it is better to support R&D as a whole as determined in standard horizontal innovation models.

This thesis draws on this background, by explicitly modeling the distinction between basic research and development in several frameworks: an economy with a unique R&D sector, an economy with two R&D sectors, differing in the relative intensity in basic research and a final set up where R&D drives growth and, within R&D, basic research also helps reducing pollution. The first two adopt the linear paradigm, therefore there is no feedback effect from applied knowledge to fundamental research. However, as literature on R&D identifies another paradigm where feedback are allowed and as both have been proven to hold, the last set up focus on the dynamic paradigm with feedback. All frameworks develop a multistage R&D process following what has been designed and applied in R&D management literature, according to Figure 1.4 above.

With respect to the linkage between R&D and pollution, we would like to remark that we take a novel approach hinging on an increasing bulk of literature on innovation management and R&D policy (EPA[10], 2005): in fact, there is an increasing awareness about the potential technological convergencies of some innovations developed by firms and environment preservation. To provide one example, nanotechnology allows creation of new materials, products and processes which have a positive side effect in pollution-abatement. However, these innovations, mostly created by firms, have not been generated with the precise aim of benefitting

[10] US Environmental Protection Agency

the environment, as the goal driving the R&D efforts is profits and increased competitiveness. Other important sectors where R&D has generated fundamental trajectories towards environmental protection, though accidentally, are manufacturing and chemical industry.

It has been estimated that the environmental trajectories of nanotech, chemical and manufacturing R&D lead to a potential energy savings for US close to 14.5% of total US energy consumption per year as outlined in Table 1(EPA, 2005): lighter materials for vehicles, materials and geometries that contribute more effectively to temperature control, technologies changing manufacturing processes, materials that contribute to new generations of fuel cells and a potential hydrogen economy (EPA, 2005) No one of these technologies have been developed for environmental care and they rely heavily on basic research.

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Nanotechnology Application	Estimated Percent Reduction in Total Annual US Energy Consumption
Strong, lightweight materials in transportation	6.2
Solid state lighting	3.5
Self-optimizing motor system	2.1
Smart roofs	1.2
Novel energy-efficient separation membranes	0.8
Energy efficient distillation through supercomputing	0.3
Molecular-level control of industrial catalysis	0.2
Transmission line conductance	0.2
Total	**14.5**

Table 1. Potential US Energy Savings from Eight Nanotechnology Application

We have tried to develop a framework suitable to capture the main differences between research and development, embedding them in an economy where R&D drives growth. We have chosen to rely on a well-established horizontal innovation set up which we modify to allow for the distinction between basic research and development along the lines we have presented above Therefore, we start from the seminal works done in horizontal innovation (Romer 1990; Rivera-Batiz and Romer 1991) inside which we insert multi-stage R&D and its consequences. Then we try to embed also the learning-by-doing feature linking basic research usage to a constant and indirect improvement of scientists within R&D. Then, to

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address multi-industry issues, we turn to the recent development on multi-sector economies based on horizontal innovation (Gancia and Zilibotti, 2003) and we also explore the issue of imitation and international R&D spillovers. Finally, acknowledging both the increasing interest among growth theorists of embedding environmental considerations within growth theory and the recent bulk of evidence about the important side-effects of basic research (also privately-performed) on pollution reduction, we tackle this issue merging horizontal innovation literature, sustainable growth contributions and multi-stage R&D.

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CHAPTER 2

BASIC RESEARCH AND THE SCALE EFFECT IN A GROWING ECONOMY

"When Charles Stine made his presentation to the Executive Committee of Du Pont in 1926, he argued that fundamental research was necessary because "applied research is facing a shortage of its principal raw materials" -P.E.Stephan Andrew. Young School of Policy Studies, Georgia State University

2.1 Introduction

The framework developed in this Chapter relies on a well-established horizontal innovation economy which has been modified to allow for the distinction between basic research and development along the lines presented in the introductory chapter. In particular, R&D is modelled as a multi-stage process where research output is used as an input in development activity, following confirmed and popular models in R&D literature (Bodner *et al* 2005). Empirical and anecdotal evidence support this analysis.

We have to remember that basic research is characterized by several features which may create market distortions (Nelson, 1959; Link *et. al.,* 1981; Pavitt, 2001) and that we have to account for the following elements: *(i)* basic research is the R&D activity whose output

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is the most likely to fail to be directly economically exploitable to produce new intermediate goods; *(ii)* the same elements implying that not all the designs developed by basic research efforts are economically exploitable, while the designs resulting from development efforts are more likely to be so, also entail that basic research is more likely to generate breakthrough innovations than development activity (Nelson, 1959; Theis and Horn 2003); *(iii)* even when a basic research design contains the characteristics of being economically exploitable, it usually needs further efforts in terms of research activities to deliver a commercially useful design (Nelson, 1959; Stokes, 1997); *(iv)* among all R&D activities, basic research generates the highest level of spillovers (*i.a.* Lichtemberg and Siegel, 1991; Funk, 2002).

Point *(iii)* summarizes the essence of multi-stage R&D process; points *(i)* and *(ii)* are important in shaping payoffs from innovation; whereas point *(iv)* introduces differences in spillover associated to each R&D components, a point that is compulsory neglected by standard horizontal innovation models, due to the homogeneity of R&D, but that matters in empirical terms.

Going more into details, in our framework, not all R&D investments will deliver positive payoffs to innovators to capture the likelihood of economically useless ideas inherent to basic research activity, but payoffs are long-lasting, as they accompany breakthrough innovation. Then, basic research generates inter-sector spillovers affecting productivity in final good production, whereas spillovers from development are just intra-sector.

With respect to multi-stage R&D patterns, in this chapter we will stick to the "linear paradigm": basic research output is used as intermediate input in development activity and

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there are no feedback from development to basic research.

The first major result of this framework is the absence of the so-called "scale effect": if the labour endowment of the economy changes, the growth rate of the economy is unaffected. Standard horizontal innovation models are generally influenced by the scale effect, a feature which has been widely criticized as it lacks empirical support (Barro and Sala-I-Martin, 2004; Jones 1995). In this model the scale effect disappears endogenously, allowing to conclude that the introduction of multi-stage research processes with intra and inter-sector spillovers contributes to better predictions.

The consequences of distinguishing basic research from development influence also the growth rate. First, productivity of each research step does not influence growth.

Another finding refers to R&D technology: if the technology of the final R&D stage relies heavily on basic research, then the economy grows more as the production of every new variety is associated with a bigger size for the positive spillover effect from basic research.

The last relevant finding refer to industrial policy for R&D. First, our model predicts that the Government should commit to patronize research fields with a level of economic exploitability which is not extremely low. Second, private agents determine an equilibrium which is not Pareto optimal as a consequence of different distortions influencing the economy. In terms of R&D policy, the Government could induce the private sector to attain the social optimum by engineering a tax-subsidy policy where basic research only receives support, even tough all R&D activities exert externality effects throughout the economy. So, according to our analysis, subsidizing R&D as a whole will prove to be a wrong policy whenever firms

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pursue multi-stage R&D.

In the final section we introduce learning-by-doing by scientists: we take into account the fact that scientists working with basic research ideas benefit from new fundamental discoveries with respect to their productivity. This amount to add a new channel through which basic research positively influences the economy. With respect to this new formulation, we find that the decentralized equilibrium does not change, as private agents fail to internalize the externality. Then, even tough differences arise with respect to first best outcomes, optimal fiscal policy states even strongly that basic research only needs support

The paper is organized as follows: Section 2 describes the economy. Section 3 analyzes the decentralized equilibrium. Section 4 presents the Social Planner outcome and some welfare considerations about optimal fiscal policy. Section 5 introduces learning-by-doing by scientists working with basic research. Section 6 concludes.

2.2 The Economy

As we have argued in the introduction, we have to distinguish basic research from development along the following lines: *(i)* basic research is the preliminary step of a multi-stage research process where development is the last one; *(ii)* basic research generates positive spillovers affecting the economy across sectors; *(iii)* spillovers associated to development activity are weak and do not spur across different sectors. Points *(i)* to *(iii)* affect the economy in many ways: by changing the structure of payoffs from R&D efforts with respect to standard horizontal innovation literature, by exerting spillovers effects on technology of good

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production and by changing the structure of the research process. These new elements need to be introduced inside an horizontal innovation framework.

We briefly recall that standard horizontal innovation frameworks consider R&D as a single step activity with either no or intra-sector spillovers. Therefore, standard models should be used to describe an economy performing only development activity, even if there would be still a drawback consisting of the perpetual monopolistic payoffs that each innovator enjoys. These are more consistent with basic-research-intensive designs (Nelson,1959). This disadvantage has already been pointed out in the literature (Barro and Sala-I-Martin, 2004) and it has been mastered through the introduction of erosion of monopolistic power to account for imitation and close substitution effects. In the set up developed in this chapter, since only basic-research-intensive activity is performed, erosion is ruled out by assumption.

The economy has a unique multi-stage R&D sector: first, firms perform basic research, then basic research output is employed in the second research activity to produce an applied design for a new variety of intermediate good. Research activities generate spillovers: basic research exerts an inter-sector effect on final good production, whereas development affects its own productivity only. Finally, a given research investment may generate economically useless designs. As usual, intermediate goods are used in the production of the final good forever. Final good is used for consumption and input in some sectors. The following figure highlights the structure of the economy[1]

[1] Upward pointing white arrows show the sequence of processes needed to produce final output in sector D and R respectively. Gray arrows highlight the different purposes of final output. Dotted arrows show the direction of externalities.

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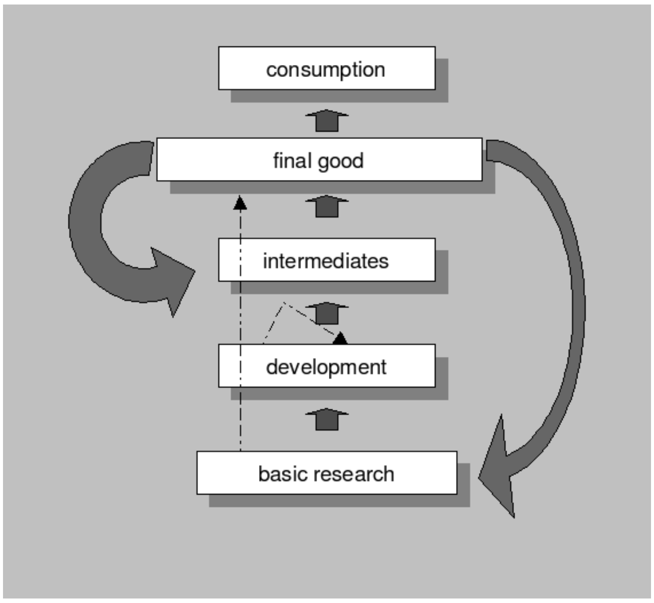

Figure 2.1. Structure of the Economy.

2.2.1 Set up

There are three types of agents in the model. Households maximize utility subject to their budget constraint. They hold shares of intermediate sector firms, supply labour and invest in new ideas. Final good producers hire labour and intermediate goods and combine them to produce a final good, which is sold at unit price. This final good serves different purposes: consumption, input for intermediate good production and input for basic research activity. Development does not use final output as input, since it transforms basic research ideas into applied designs using only basic research and labour as costly inputs.

R&D firms devote resources to discover new designs. Differently from standard horizontal innovation set up, here we deal with basic-research-intensive designs only. This focus implies that the unique R&D process is made of two steps, each one characterized by a specific technology. We assume that there is uncertainty with respect to exploitability of the final design coming from the manipulation of basic research ideas. This assumption is consistent to the literature, since we are accounting for the fact that fundamental discoveries which are realized without any specific economic aim may fail to be useful to create a new product or process. This failure is revealed only after further research is applied to the basic research idea.

Firms choose whether to enter or not, knowing in advance the characteristics of the economy. All designs and ideas are patented and they are subject to the same law. To this respect, we keep the standard assumption about perpetual patent: once a design has been patented, the owner of the patent holds the exclusive and perpetual right about its potential economical exploitation.

2.2.2 The model

Final good sector. Producers of final good have access to a production technology combining a number of intermediate inputs and labour to produce final output, which is then sold in the market at unit price. Formally,

$$Y = \left(\int_0^{lN} x_j^{\alpha} dj \right) E_Q^{1-\alpha} L_Y^{1-\alpha} \tag{2.1}$$

where $0 < \alpha < 1$. Final good sector aggregates in a Cobb-Douglas fashion two costly inputs: intermediate goods, x_j and labour, L_Y. x_j is the employment of the jth type of intermediate good and lN is the total number of varieties of intermediates in the economy. Note that

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lN does not corresponds to the total stock of designs produced, which is given by N. This happens because not all the designs obtained transforming basic research ideas are economically exploitable. To this respect, we assume that there is a probability l, $0 < l < 1$, that the transformation of basic research ideas into designs gives a patent which allows for a new variety of intermediate good. At each point in time we have N designs obtained from the transformation of basic research ideas. Out of this stock, only a fraction allow for new varieties of intermediate goods. For the law of large number, this fraction equals lN.

Final good production is affected by a positive externality, E_Q, determined by the array of basic research available to new innovators. This assumption relies on the level of generality of this research activity which allows for inter-sector spillovers, as pointed out both in the literature and in the empirical evidence (Funk, 2002; Lichtemberg 1990).Consistently with empirical evidence on R&D spillovers, we assume that the externality depends positively on basic research, Q, (Lichtemberg, 1990). Then, following other well-established works, we assume that basic research propagates across the economy through the interactions between scientists and other workers (Lucas, 1988). Therefore, we can assume that the positive externality effect is played by the *average* level of basic research, $\frac{Q}{L_N}$, where L_N are total scientists working with basic research, rather than by the *aggregate* level, as spillovers get influenced by the quality of scientists that final good workers meet. Finally, we assume that patent owners exert some noise around basic research ideas trying to enforce some secrecy to preserve strategic and costly inputs for new designs. We model these efforts as proportional to the size of sector, N. This assumption hinges on the key relevance of basic research in

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ensuring high and long-lasting payoffs for firms and on the fact that here basic research is entirely performed by private firms. The latter feature implies that in this economy basic research cannot be thought as a knowledge whose task is to be spread among scientists to fuel debates and further research and that secrecy about key discoveries is important to fully exploit their economic potential. In other words, efforts carried on by firms to preserve strategic and costly inputs for new designs prevents close substitutes to arise. Note that this environment is consistent with evidence about privately performed basic research (Audrestch *et al*, 2002). Therefore, the externality is given by[2]

$$E_Q = \frac{Q}{NL_N}, \tag{2.2}$$

Final good is used for consumption, input for the production of intermediate goods and input for creation of basic research ideas. We take the price of Y as the numeraire.

Intermediate good sector. Following horizontal innovation literature, each intermediate good producer holds a patent which grants the exclusive right to produce a specific variety of intermediate good. Every patent allowing for a new variety grants perpetual monopolistic profits to producer. However, in our set up, buying a patent does not guarantee positive payoffs with certainty, since the patent may turn out to be non-exploitable to produce a new intermediate good.

We assume that an intermediate good , once invented, costs one unit of Y to produce

[2] Alternatively, we could express the externality as a positive function of the average level of basic research per innovator and a negative function of scientists.

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and, as eq.(2.1) shows, it is used in the production of final good forever.

Research Firms. New firms wishing to enter intermediate good production must invest in research first. An entrant has to do basic research first and then to use its output as an input to try to get a useful design for a new variety of intermediate goods. Therefore, entry implies a bigger research effort, whose output may end up being economically useless. Moreover, entry obliges firms to go through all the research stages before knowing whether their investment leads to a positive payoff or not. This two-stage research process captures both the idea that a basic research design leads to production of goods only if some applied research activity is performed afterwards and that creating breakthrough innovation is not as easy as innovating along existing knowledge. As explained in the introductory chapter, for simplicity we assume that applied research is comprised partly inside basic research and partly inside development.

Firms face the two stage decision process typical of standard models of horizontal innovation. First, they decide whether to enter or not. Entrants will invest in R&D if the market value of the firm producing the new variety of intermediate good is at least as large as the R&D expenditure they have to bear to start the firm. Then, they decide the optimal price at which to sell their new intermediate goods to final good sector firms. This price determines the demand they face and, as a consequence, the expected future profits. The two stage problem is solved backward. First, the optimal price for new intermediate good is determined under the assumption that a new design which translates into a new good has already been invented. Then, the value of the firm is found and compared to the R&D cost.

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Since free entry into the business of being an inventor is assumed, we will deal with a free entry condition that holds in equilibrium such that entry occurs when the market value of the firm equals the R&D cost.

The market value of a new intermediate good firm is given by $V = \int_t^{\infty} e^{-\int_t^s r(\tau)d\tau} E_t \pi(s) ds$,where π are the instantaneous profits from intermediate good production and E_t is the expectation operator, conditional on information at time t. Expected profits at time s as seen from time t from entry are $E_t \pi(s) = l\pi$, since an exploitable design granting perpetual monopolistic profits happens with probability $l, 0 < l < 1$. An intermediate good costs one unit of Y to produce, therefore, profits accruing to firm producing variety j are given by $\pi_j = (\tilde{p}_j - 1)x_j$, where $\tilde{p}_j$ is determined by profit maximization in the final good sector. The market values for a new intermediate good firm is given by

$$V = l\frac{\pi}{r}. \tag{2.3}$$

We assume a R&D cost determined by R&D firms profit maximization problems. The R&D cost that entrants must pay corresponds to the price of a new patent. This price is determined by R&D firms according to their two-step technology. We determine the price considering the maximization problem of the i-th firm in the R&D sector, which follow from the R&D process structure developed by R&D management literature and described in the introductory chapter (Bodner *et al.,* 2005).

To generate a final blueprint that can be sold in the market to entrant firms, the R&D

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firm i must undertake its specific basic research, according to the following technology

$$q_i = \frac{1}{\eta} M_i, \tag{2.4}$$

where η is an exogenous productivity parameter and M_i is the amount of final output used by firm i in basic research production. Basic research ideas, q_i are then used as input in another research activity, which transforms them in attempt to produce a new exploitable design according to

$$b_i = (1-l)^{\beta} (N L_{Ni})^{\beta} q_i^{1-\beta} \tag{2.5}$$

where b_i corresponds to the single new blueprint produced by R&D firm i.

Having analyzed the problem of firm i, we need to reach the aggregate level of the R&D sector, to determine how knowledge evolves in the economy. At the aggregate level there are $\dot{N}$ identical innovators, therefore eq.(2.4) and (2.5) and a symmetry assumption show that new development designs evolve according to

$$\dot{N} = \frac{(1-l)^{\beta}}{\eta^{1-\beta}} (N L_N)^{\beta} M^{1-\beta}. \tag{2.6}$$

As eq.(2.6) shows, final designs accumulate thanks to basic research ideas and labour, L_N. Then there is a positive externality given by the stock of useless final designs produced in the sector, $(1-l)^{\beta} N^{\beta}$.

Empirical evidence on R&D spillovers shows that basic research exerts the biggest and most pervasive externality effects, both inter and intra-sector. The size and the pervasiveness

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of spillovers declines significantly when we consider development. Therefore, our assumption about spillovers due to the different components of R&D is consistent with the data.

Households. Households maximize utility over an infinite horizon. They are endowed with constant aggregate flows of labour which they supply inelastically, $\bar{L} = L_N + L_Y$. Their objective function is given by

$$U(C) = \int_0^\infty \left(\frac{C^{1-\sigma} - 1}{1-\sigma} \right) e^{-\rho t} dt$$

Households receive a wage rate on labour and returns from assets. They discount the future at rate ρ. Their budget constraint is given by

$$C + \dot{a} = w_Y L_Y + w_N L_N + ra,$$

where a denotes households'assets. The consumption plan they set when maximizing utility subject to the constraints satisfies standard Euler equation

$$\frac{\dot{C}}{C} = \frac{1}{\sigma}(r - \rho). \tag{2.7}$$

2.3 Decentralized equilibrium and BGP

2.3.1 BGP

As a consequence of the modifications that we have introduced, we need to check whether the growth rates of the number of intermediates, lN, of the number of designs, N, of basic

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research ideas, Q and of the level of output, Y still equal the growth rate of consumption. To this respect, the following Proposition holds.

Proposition 2.1 *As long as all R&D activities grow at the same rate, that is* $\frac{\dot{N}}{N} = \frac{\dot{Q}}{Q}$, *then all variables in the economy will grow at the same rate given by*

$$\frac{\dot{N}}{N} = \frac{(1-l)^{\beta}}{\eta^{1-\beta}} L_N^{\beta} \left(\frac{M}{N}\right)^{1-\beta} \tag{2.8}$$

Proof. See the Appendix. ■

Now, we need to find the equilibrium expression for this growth rate, therefore, we need to solve for the decentralized equilibrium.

2.3.2 Decentralized Equilibrium

Profits from final good production are given by

$$\max_{\{x\}_{j=0}^{lN}, L_Y} E_Q^{1-\alpha} \left(\int_0^{lN} x_j^{\alpha} dj\right) \left(\bar{L} - L_N\right)^{1-\alpha} - w_Y \left(\bar{L} - L_N\right) - \int_0^{lN} \tilde{p}_j x_j dj$$

w is the wage rate for labour, $\tilde{p}_j$, is the price of the jth monopolized intermediate good. Final good sector is competitive, therefore input prices are taken as given. Instantaneous profit maximization gives the following first order conditions, once symmetry has been imposed

$$\tilde{p} = E_Q^{1-\alpha} \alpha x^{\alpha-1} \left(\bar{L} - L_N\right)^{1-\alpha}, \tag{2.9}$$

$$w_Y = (1-\alpha) lN E_Q^{1-\alpha} \left(\frac{x}{\bar{L} - L_N}\right)^{\alpha} \tag{2.10}$$

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Eq.(2.9) is the inverse demand functions faced by intermediate good producers. Recall that an intermediate good, no matter its type, once invented, costs one unit of Y to produce; this assumption together with the demand functions allows to write the profit flows for intermediate goods. If we deal with the jth monopolized intermediate good, the profit flow is given by $\pi_j = (\tilde{p} - 1) x_j$, where $\tilde{p}$ is given by eq.(2.9). Since monopolists set marginal revenues equal to marginal cost, we get $\tilde{p} = \frac{1}{\alpha}$ and $x = \alpha^{\frac{2}{1-\alpha}} \left(\frac{Q}{NL_N}\right) \left(\bar{L} - L_N\right)$.Therefore, symmetry across all the monopolized intermediate goods implies that

$$\pi_j = \pi = \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} E_Q \left(\bar{L} - L_N\right) \tag{2.11}$$

Monopolistic profits represent the positive payoffs from R&D investment, thus providing the right incentive to innovate.

R&D firms auction their final blueprints to a large number of potential buyers, thus absorbing all the profits of the intermediate good sector through the blueprint price $\hat{p}$ (free entry condition). Therefore,

$$V = \hat{p} \ , \tag{2.12}$$

where, according to eq.(2.3), $V = \frac{l\pi}{r}$, with π given by eq.(2.11). R&D firms are competitive and they generate final blueprints using labour and basic research plus an externality effect played by the stock us useless final blueprints. We assume that they produce basic research ideas rather than purchasing them from outside. Basic research is produced according to eq.(2.4). Firms pay the wage rate, w_N, for each unit of industry-specific labour unit they

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hire and they purchase final output at unit price to produce basic research. Shareowners receive firms' net cash flow as dividend. Firms'objective is to maximize profits. Formally,

$$\max_{M,L_N} \hat{p}(1-l)^{\beta} N^{\beta} q_i^{1-\beta} L_{Ni}^{\beta} - M_i - w_N L_{Ni}$$

subject to eq.(2.4).

First order conditions, together with symmetry, imply

$$\hat{p} = \frac{\eta^{1-\beta}}{(1-\beta)(1-l)^{\beta}} \left(\frac{M}{N}\right)^{\beta} L_N^{-\beta}, \tag{2.13}$$

$$w_N = \hat{p}\frac{\beta(1-l)^{\beta}}{\eta^{1-\beta}} N \left(\frac{M}{N}\right)^{1-\beta} L_N^{\beta-1}. \tag{2.14}$$

In equilibrium, wages must be equal. We set eq.(2.10) equal to eq.(2.14) and we solve for $\hat{p}$. We get

$$\hat{p} = \frac{\eta^{1-\beta} l(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}}{\beta(1-l)^{\beta}} E_Q \left(\frac{M}{N}\right)^{\beta-1} L_N^{1-\beta}. \tag{2.15}$$

Eq.(2.15) is the price for a final design which we use in the free entry condition, $\hat{p} = \frac{\pi}{r}$, together with eq.(2.11), to determine the equilibrium expression for the interest rate.

$$r_{entry} = \frac{\alpha\beta(1-l)^{\beta} \left(\frac{M}{N}\right)^{1-\beta} \left(\bar{L} - L_N\right) L_N^{\beta-1}}{\eta^{1-\beta}}. \tag{2.16}$$

Recall that, in equilibrium, all variables grow at the same rate. Then, eq.(2.8) and the

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Euler equation, eq.(2.7), give another expression for the interest rate

$$r_{savings} = \frac{\sigma(1-l)^{\beta}}{\eta^{1-\beta}} L_N^{\beta} \left(\frac{M}{N}\right)^{1-\beta} + \rho. \tag{2.17}$$

Then, using non arbitrage in asset market, we set eq.(2.16) equal to eq.(2.17), solving for $\frac{M}{N}$,

$$\left(\frac{M}{N}\right)^{1-\beta} = \frac{\rho\eta^{1-\beta}}{(1-l)^{\beta}\left[\alpha\beta\left(\frac{\bar{L}-L_N}{L_N}\right)-\sigma\right]L_N^{\beta}}. \tag{2.18}$$

The fact that basic research is both a costly input and a source of spillovers in the final good sector imply that $\frac{M}{N}$ depends negatively on total labour force: intuitively, an increase in the labour force determines an increase in N, through an increase in L_N. As a consequence, $\frac{M}{N}$ decreases.

Finally, we need to determine the equilibrium value for labour allocation. To find it, we set eq.(2.13) equal to eq.(2.15) and we solve for L_N,

$$L_N^{\beta} = \frac{(1-\beta)(1-\alpha)l\alpha^{\frac{2\alpha}{1-\alpha}}}{\eta^{1-\beta}(1-l)^{\beta}\beta}\left(\frac{M}{N}\right)^{\beta-1}, \tag{2.19}$$

which we use in eq.(2.18) to find the equilibrium expression for L_N. Then, by substituting the resulting expressions for L_N and $\frac{M}{N}$ inside the BGP growth rate we find[3]

$$\gamma = \frac{(1-\alpha)(1-\beta)l\alpha^{\frac{2\alpha}{1-\alpha}}}{\beta}. \tag{2.20}$$

[3] Trasversality condition in this kind of model is $r > \gamma$, which holds as long as $\rho > \frac{(1-\sigma)(1-\alpha)(1-\beta)l\alpha^{\frac{2\alpha}{1-\alpha}}}{\beta\eta}$.

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Therefore, the following Proposition is verified:

Proposition 2.2 *The economy is characterized by a unique interior solution, without any scale effect.*

2.3.3 The Scale Effect

As highlighted by Proposition 2, the most evident consequence of the introduction of a multi-stage research process is the absence of any scale effect on the growth rate. This finding is important, since there is no empirical evidence supporting the positive scale effect of population on growth which characterizes many contributions in the horizontal innovation literature (Barro and Sala-I-Martin, 2004; Jones 1999).

Note that each research stage has been shaped using the most-widely-adopted functional forms in horizontal innovation literature: basic research is described by a standard "lab-for-equipment" technology (Rivera-Batiz and Romer, 1991) which we have enriched with an externality, whereas development is modelled through the benchmark technology used by Romer in his seminal contribution on horizontal innovation and further developed (Gancia and Zilibotti, 2003). Both technologies, when used alone, deliver growth rates with scale effects. In fact, in the benchmark model (Romer, 1990), the growth rate of knowledge is given by $\gamma_{Romer} = \frac{1}{\eta} L_{R\&D}$, where γ_{Romer} is the BGP growth rate in the model and $L_{R\&D}$ is the amount of total labour devoted to R&D. Then, as the economy is characterized by a unique Balanced Growth Path with positive and constant growth, in equilibrium we have $L_{R\&D} = m\bar{L}$, $0 < m < 1$, and γ_{Romer} proportional to $\bar{L}$. In the "lab-for-equipment" model,

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the rate of return is given by $r = \delta \bar{L}$ and uniqueness of growth rate along the BGP implies that $\gamma_{Lab-Equip} = \frac{1}{\sigma}(r - \rho)$.

Under both scenarios, the scale effect is due to the fact that a new variety, which is costly to invent, can be used in a non rival way across the whole economy; therefore, the larger the economy, the lower the cost on an invention per unit of economic activity, proxied by Y. In equilibrium, the cost of an invention per unit of economic activity depends negatively on the size of the population leading to the result that an increase in the size of the population has the same effect on the growth rate as an equiproportionate decrease in the R&D cost. In our framework, the cost of performing R&D per units of economic activity, $\frac{\hat{p}}{Y}$, is independent from the scale of the population along the BGP. Therefore, any change in population size does not affect the cost of an invention per unit of economic activity and, as a consequence, does not influence the growth rate.

The mechanism through which we reach this result is described in the following Lemmas

Lemma 2.3 *As long as in equilibrium, (i) labour allocated to development is a fraction of total labour,* $L_N = m\bar{L}$, $0 \leq m < 1$; *(ii) the R&D is process specified by eq.(2.4) and eq.(2.5); (iii) the economy is along the Balanced Growth Path, then the scale effect disappears as the effect of* $\bar{L}$ *on* $\hat{p}$ *is offset by the effect of* $\bar{L}$ *on entry payoffs.*

Proof. Consider R&D firm first order condition for wage, eq,(2.14). Solving for $\hat{p}$ and using non arbitrage in the labour market we get eq.(2.15). Then, consider eq.(2.11). Applying

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free entry and assuming that in equilibrium, $L_N = m\bar{L}$, $0 \leq m < 1$ we get

$$r_{entry} = \frac{\alpha\beta(1-l)^{\beta}}{\eta^{1-\beta}} \left(\frac{1-m}{m}\right) \left(\frac{M}{N}\right)^{1-\beta} L_N^{\beta}.$$

Then, using eq.(2.18),

$$r_{entry} = \frac{\alpha\beta(1-l)^{\beta}}{\eta^{1-\beta}} \left(\frac{1-m}{m}\right) \frac{\rho\eta^{1-\beta}}{(1-l)^{\beta}\left[\alpha\beta\left(\frac{\bar{L}-L_N}{L_N}\right)-\sigma\right]}$$

■

This Lemma shows that, as long as $L_N = m\bar{L}$, $0 \leq m < 1$, the scale effect disappears thanks to multi-stage R&D, with a growing input and a constant one used in a Cobb-Douglas way and development externality. This specification for development technology makes the entry cost depend on the same inputs needed to discover a new variety and following the Cobb-Douglas proportions which determine also the BGP growth rate. R&D do not have any effect.

Note that we have assumed $L_N = m\bar{L}$, $0 \leq m < 1$. This condition is necessary to rule out the scale effect in Lemma 2.3. In this framework this is indeed true in equilibrium according to the following Lemma.

Lemma 2.4 *In this economy, as long as (i) R&D is given by eq.(2.4) and eq.(2.5), (ii) the economy is along the Balanced Growth Path; (iii) there are positive basic research spillovers given by eq.(2.2), then in equilibrium* $L_N = m\bar{L}$, $0 \leq m < 1$.

Proof. Eq.(2.4) and eq.(2.5) determines eq.(2.13) and (2.14). In equilibrium, $w_N = w_Y$.

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Using eq.(2.10) we reach eq.(2.15). We find a system of two equation in $\hat{p}$: eq.(2.13) and eq.(2.15). Solution of the system gives eq.(2.19), where $L_N = L_N(M, N)$. We then build a system with eq.(2.18) and eq.(2.19) to get $L_N = m\bar{L}$, $0 \leq m < 1$. ■

Putting the reasoning in economic terms, consider the free entry condition, $r = \frac{l\pi}{\hat{p}}$ where π is defined by eq.(2.11) and $\hat{p}$, after non arbitrage in labour market has been enforced, by eq.(2.15). We see that an increase in population exerts two opposite effects on the rate of return. On the one hand, a positive shift in $\bar{L}$, by increasing demand for intermediate goods, plays a positive effect on r through an increase in monopolistic profits. This is the standard channel through which the scale effect influences equilibrium in horizontal innovation models. However, in this economy there is another channel through which the scale of the population affects equilibrium: through the R&D process inputs, M and L_N. Through this new channel, the same positive shift in $\bar{L}$ makes the price for a blueprint increase. In equilibrium, the direct effect of an increase in the labour force is completely offset by the indirect effect.

The way the scale effect is ruled out follows some attempts to remove the scale effect in learning-by-doing models with knowledge spillovers (Lucas, 1988), where the effect is eliminated by assuming that knowledge spillovers are exerted by the average level of knowledge and not by the aggregate level. Remember that here the positive effect of basic research is given by $\frac{\bar{q}}{L_N}$.

The final point about scale effect refers to comparison with other successful attempts to remove it. As defined in the literature, horizontal innovation models without the scale effect fail into two main categories: those where the growth rate of output per capita is proportional

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to the growth rate of population (semi-endogenous growth models) and those where the scale effect is ruled out assuming that an increase in the scale increases the number of varieties available, leaving the amount of research effort per sector unaltered (endogenous growth model) (Jones, 1999). In our framework, the cost of performing R&D per units of economic activity is independent from the scale of the population along the BGP. Therefore, any change in population size does not affect the cost of an invention per unit of economic activity and, as a consequence, does not influence the growth rate. So, we fall in the endogenous growth models group.

2.3.4 Comparative Statics

This set up has accounted for specific features characterizing a research process where different steps are performed. Each step produces a different kind of output and it is characterized by a specific technology.

We focus on the determinants of the growth rate. We start from noticing that productivity of development activity, captured by the term $(1-l)^{\beta}$ does not influence the growth rate. In fact, the positive effect exerted on returns from entry as seen in eq.(2.16) is completely offset by the negative effect on $\frac{M}{N}$ channelled through basic research spillovers; first order conditions in R&D production, together with eq.(2.10) imply that $\frac{M}{N}$ is related to E_Q; then, E_Q depends negatively from $(1-l)^{\beta}$, since this term, by positively affecting the size of the R&D sector, reduces the basic research to applied designs ratio.

The same argument works for productivity of basic research.

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Then, the growth rate is also affected by the technology parameter shaping R&D, β, : in particular, according to eq.(2.20), an increase in β lowers growth. From first order conditions in R&D we get the relative factor demand

$$\frac{L_N}{M} = \frac{\beta}{1-\beta}\frac{w_N}{N},$$

which shows that, ceteris paribus, if β increases, final designs are produced using relatively more development-specific inputs than basic research. As a consequence, $\frac{M}{N}$ diminishes and this, by increasing $\hat{p}$ more than π reduces payoffs from entry. Thus, the incentive to start up new firms decreases and growth is damaged[4].

We consider also the parameter governing the fraction of useful design, l. This parameter exerts two opposite effects: a positive effect on payoffs from investment in research and a negative one on productivity of development activity. Overall, an increase in l affects positively the growth rate, as the reduction in productivity within the research sector is cancelled by the increase in basic research externality through the channel described above.

The latter result gives some interesting insight in terms of R&D policy: the Government should commit to patronize research fields with a level of economic exploitability which is not extremely low. This policy advice provides a theoretical support for the R&D policy adopted in the US dated back to the beginning of the century: the Government acknowledges that basic research is a key component to keep the country leading position in economic terms

[4] The same result can be reached looking at the Technical Rate of Substitution of the development production function.

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and at the same time it is also aware that it is important to identify the fields that basic research must investigate (Stokes, 1997).

2.4 Social Planner and Optimal Fiscal Policy

In the baseline horizontal innovation framework, the decentralized equilibrium is notoriously inefficient, due to monopolistic competition and externalities. In this section we demonstrate that the outcomes determined in the decentralized economy are not Pareto optimal.

In order to assess Pareto optimality, we compare the BGP growth rate of the decentralized economy with the corresponding growth rate determined by the Social Planner. The planner maximizes the utility of the representative household taking into consideration the economy-wide resource constraint and the laws of motion for N. To this respect, the following Lemma holds.

Lemma 2.5 *The planner solution differs from the solution determined by the decentralized economy. Also in this case the scale effect does not appear.*

Proof. See Appendix B. ■

2.4.1 Optimal Fiscal Policy

Lemma 2.4, shows that the Social Planner solution is different from the decentralized one. It is important to notice that the economy is characterized by several distortions, each one exerting a specific effect on the growth rate. On the one hand, monopolistic competition

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and positive spillovers from research and development cause private agents to produce a level of output which is lower than socially optimal; on the other hand, congestion determined by the number of intermediate good producers acts as a negative externality.

Since there are distortions which do not appear in the typical horizontal innovation framework, we expect the optimal fiscal policy to contain some instruments which do not arise in benchmark models.

The policy that the Government should design to push the decentralized equilibrium towards the first best consists of three instruments: the first corrects for monopolistic competition, the second adjusts for congestion and the third for the positive spillovers from research and development.

Monopolistic competition in intermediate good production determines an allocation of resources to intermediates which is lower than socially desirable, therefore a subsidy to intermediate good purchase that induce marginal cost pricing without eliminating the proper incentive to create new varieties is the right instrument to correct for the distortion. The subsidy must be such that $(1-\theta_x) = 1-\alpha$. Note that this instrument is standard in horizontal innovation literature.

Congestion (or noise) acts as a negative externality. To reduce the negative effect, the Government curtails returns from entry in intermediate good production by taxing households' asset income at a rate given by $(1-\tau_H) = \frac{\alpha\left(\frac{L-L_N}{L_N}\right)}{1+2\left(\frac{L-L_N}{L_N}\right)}$. This tool reduces investors willingness to start new firms, thus reducing the size of N.

At the same time, private agents cannot capture the positive spillovers generated by

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basic research. As a consequence, both entry and research investment decisions do not take properly into account all the effects of basic research on the economy and the equilibrium value for basic research is lower than the social one. Then, correcting for congestion lowers private willingness to invest in R&D as it lowers returns from patent holding, but it does not discriminate among R&D activities. Therefore, it is important to find another fiscal tool such that, for a given level of entry, basic research employed in the R&D process increases. So, the Government optimally sets a subsidy for basic research production. This second subsidy reduces input cost in basic research production and is given by $(1-\theta_M) = \left[\frac{(1-\beta)}{1-\beta+\left(\frac{L-L_N}{L_N}\right)}\right]$.

This simple framework, accounting for the most important characteristics identifying a research process in which basic research is performed, shows that the presence of inter and intra-sector externalities generated by different R&D components determines an optimal fiscal policy which differs significantly from the one traditionally discussed in the literature. The first, most obvious, remark concerns R&D policy: in this economy we find that the optimal tool for R&D policy is directed towards basic research only. Development activity is not interested by any fiscal instruments, although both exert spillover effects. The intuition behind this finding is based upon the most important feature typifying basic research from development: the relative higher pervasiveness of spillovers.

Moreover, support to R&D spending, which is usually adopted with a research technology as the one we have used for development turns out to be neutral with respect to the first best.

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2.5 Learning-by-Doing

An interesting extension of this set up consists of inserting learning by doing for scientists. In other words, scientists transforming basic research into final blueprints get to produce more efficiently by getting in contact with new pieces of knowledge. Assuming that scientists work better if they become more learned sounds quite logical.

The inclusion of this feature changes the R&D process: in particular, the production of final blueprint changes as follows

$$b_i = q_i^{\delta} \left(E_{QL} L_{Ni} \right)^{1-\delta}$$

where $0 < \delta < 1$. E_{QL} is new fundamental knowledge benefitting scientists. We assume that E_{QL} is made of the bulk of new basic research ideas produced in the sector. In other words,

$$E_{QL} = M.$$

Then, the speed of accumulation of applied knowledge becomes

$$\dot{N} = \frac{1}{\eta^{\delta}} M L_N^{1-\delta}$$

The other sectors of the economy does not change from previous sections.

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2.5.1 Decentralized Equilibirum and BGP

We are still dealing with an economy where, as long as R&D components grow at the same rate, then all variables grow at the same constant rate, given by[5]

$$\frac{\dot{N}}{N} = \frac{1}{\eta^{\delta}} \frac{M}{N} L_N^{1-\delta}. \tag{2.21}$$

A different technology for final blueprint implies changes in patent prices and, as a consequence, modifications in entry conditions. To determine the effects of these modifications, we have to find the R&D cost in the new set up and to use it to find the equilibrium value for the rate of return.

First, eq.(2.10) to eq.(2.12) still hold. Then, we solve for the R&D firm profit maximization problem with the new specification for development activity

$$\max_{M, L_N} \hat{p} q_i^{\delta} \left(E_{QL} L_{Ni} \right)^{1-\delta} - M_i - w_N L_{Ni}$$

subject to eq.(2.4). FOCs for this problem are given by

$$\hat{p} = \frac{\eta^{\delta}}{\delta} M^{1-\delta} \left(E_{QL} L_N \right)^{\delta - 1} \tag{2.22}$$

$$\hat{p} = w_N \frac{\eta^{\delta}}{(1-\delta)} M^{-\delta} L_N^{\delta} E_{QL}^{\delta-1}. \tag{2.23}$$

As before, we use non arbitrage in the labour market to subsitute for w_N. We then set the

[5] This claim is analoguous to Proposition 2.1 and the same proof holds.

resulting expression equal to eq.(2.22) and we solve for the basic research-applied knowledge ratio

$$\frac{M}{N}=\frac{(1-\alpha)l\alpha^{\frac{2\alpha}{1-\alpha}}\eta^{\delta}\delta}{(1-\delta)}L_N^{\delta-1},$$

that we substitute inside eq.(2.21) to find the equilibrium value for the growth rate

$$\gamma_{learning}=\frac{(1-\alpha)l\alpha^{\frac{2\alpha}{1-\alpha}}\delta}{(1-\delta)}. \tag{2.24}$$

It is straighforward to notice that eq.(2.24) equals eq.(2.20).

2.5.2 Social Planner and Optimal Fiscal Policy

With respect to the economy described in the previous sections, here we deal with a further positive spillover effect exerted by basic research. Then, we neglect spillover effects from development. The Social Planner solution differs from the BGP growth rate determined by private agents and summarized by eq.(2.24)[6]. Moreover, it also differs from the first-best solution from the previous section. So, although private agents' failure in internalizing spillovers leads the two economies to have the same decentralized growth rate, the differences in externality trajectories imply different first best allocations.

As basic research generates two trajectories for positive externalities, targeting final good with E_Q and scientists with E_{QL}, we find that it is optimal to subsidize basic research through input purchase at rate $(1-\theta_Q)=\delta$ and to subsidize employment in final good production at rate $(1-\theta_{LY})=1+(2-\delta)\frac{\bar{L}-L_N}{L_N}$. The latter is equivalent to a tax to scientists employment

[6]The detailed solution of the Social Planner's problem is presented in Appendix D.

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in R&D.

Finally, monopolistic competition in intermediate good supply calls for a subsidy to intermediate good purchase: $(1-\theta_x) = 1-\alpha$.

Therefore, a decentralized economy where basic research is able to exert spillovers both on final good production and on scientists productivity can be tracked back to an economy where basic research exerts spillovers only on final good production. This happens because private agents fail to internalize any kind of spillovers, so, being them either one or two do not make any difference in their allocation choice.

However, differences in the trajectories of basic research externalities matters in term of first best allocations: the first best outcome without learning-by-doing differs from the one with learning-by-doing.

With respect to optimal fiscal policy, the menu of optimal fiscal instruments provides a stronger support to the importance of disentangling basic research from development, as this set up recommends both support to basic research and taxation to development.

2.6 Conclusion

Both economic literature and historical evidence highlights that the distinction between basic research and development is important because they are endowed with different characteristics that may play significant roles in determining the economic outcomes and effect of R&D in an economy. However, horizontal innovation literature has thus far neglected these issues and their consequences on growth.

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This paper has addressed this topic by explicitly modelling R&D as a multi-stage process, made of consequent steps each one characterized by specific economic features in a typical R&D-based model of endogenous growth.

The first element worth noticing is that disentangling basic research from development allows to model spillovers associated to R&D according to both economic literature and empirical evidence: the most significant spillover effects are related to basic research and they spur throughout the economy; development activity is characterized by small spillovers, mainly directed towards R&D itself (*i.a.* Funk, 2002; Kesteloot and Veugelers, 1995; Lichtemberg and Siegel, 1991). More generally, the specification adopted in this paper allows for a representation of R&D carried on at firm level (BERD) which is close to the data and to well-established models of R&D process.

As a consequence of this approach, the model presents some interesting insights which do not appear when R&D is treated as a homogeneous good.

The first result refers to the scale effect. Models with an expanding variety of products generally imply equilibrium outcomes which depend on the size of the population: the bigger the size, the more the economy grows. This implication has been criticized empirically because the rate of productivity growth has been relatively stable despite upward trends in population size (Jones, 1999). As a consequence, many contributions have been made to get rid of the scale effect in horizontal innovation economies. In this economy, the realistic assumption about multi-stage research processes with the inherent possibility of modelling basic research spillovers contribute to eliminating the scale effect through two different steps.

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We have seen that both features are necessary to reach an equilibrium where the cost of performing R&D per units of economic activity is independent from the scale of the population. To this respect, our economy resembles a model of learning-by-doing with spillovers where the scale effect is eliminated as firm's knowledge depends on the economy average capital per worker (Lucas, 1988). We manage to keep an endogenous growth framework.

Then, the introduction of multi-stage research processes where the final step uses the stock of ideas produced in the previous one as a costly input provides some non obvious results also in terms of determinants of the growth rate. In particular, productivity of each steps has different effects on growth, being basic research productivity the one playing overall positive effects. Moreover, it is better for growth if the final R&D stage handles relatively more basic research among all the inputs. Therefore, the positive effects linked to peculiar characteristics of basic research have indeed important consequences on growth, whereas development specific features do not have the same impact.

Some interesting implications arise also with respect to R&D policy. The decentralized outcome fails to be Pareto optimal as we are dealing with monopolistic competition, positive spillovers from basic research and congestion from attempts to keep secrecy around fundamental discoveries and noise due to "stupid" scientists. While monopolistic competition and positive spillovers implies that private agents allocate fewer resources than socially optimal, congestion causes the reverse.

The optimal fiscal policy deals with the whole set of distortions, presenting fiscal tools which differ significantly from previous results. Along with typical corrections for monopo-

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listic competition, the optimal fiscal menu consists of two more subsidies. One corrects for congestion, while the other for basic research spillovers.

Since basic research is the unique R&D activity deserving fiscal aid, the model provides theoretical support to both literature and policy advocating that basic research, among all R&D activities, needs the strongest aid. This result provides also theoretical support for the adoption of fiscal aid to R&D mainly directed towards basic research, a kind of policy which has been undertaken by US Government in past years (NSF, 2004) and that is now debated in many European countries.

It is important recalling that in standard horizontal innovation literature either there is no need for subsidizing research (*i.a.* Rivera-Batiz and Romer, 1991) or fiscal support goes generically to R&D (*i.a.*Romer, 1990). These results are mainly due to the fact that R&D is treated as homogeneous.

Finally, the model contains another policy advice about R&D. Among other features, R&D is characterized by the possibility that out of a certain investment, the output may be economically useless. This feature is particularly true when basic research is performed, since it starts a research process by exploring the unknown. To account for this feature, we have assumed that a fraction of R&D output does not deliver any new variety of good. In equilibrium a reduction in the fraction of economically useless designs benefits the growth rate, by increasing returns from R&D investments. Going back to the real world, data show that many Governments affect the kind of R&D performed in the economy -also when privately performed- by patronizing some research fields instead of others. To this respect,

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this model suggests that such policy should consider the likelihood of economic exploitability of research investments per fields, choosing to campaign research fields with a probability of delivering positive payoffs for investors that is not too low. To this respect, the model gives a theoretical support for the main features of US R&D policy, which has always campaigned the key role of basic research investments, but it has also determined the fields to explore.

We have also accounted for the fact that scientists working with basic research ideas benefit from new fundamental discoveries with respect to their productivity. So, we insert a novel trajectory through which basic research positively influences the economy: learning-by-doing. With respect to this new formulation, we find that the decentralized equilibrium does not change, as private agents fail to internalize the externality. Then, even tough differences arise with respect to first best outcomes, optimal fiscal policy states even strongly that basic research only needs support.

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2.7 Appendix A: Economy-wide Resource Constraint

Households' budget constraint is given by

$$C + \dot{a} = w_Y L_Y + w_N L_N + ra$$

where a denotes households' asset. In this economy, assets consist of the shares of intermediate good firms and shares of R&D firms. Since the economy is closed, households own the total number of shares and asset returns are given by the total value of claims on firms. The value of a claim on intermediate good producing firms at time t is given by V_N. Thus, the aggregate value of claims on intermediate good firms owned by households is equal to $rlV_N N$. Then, owning claims on R&D firms makes households enjoy the aggregate net cash flow generated by those firms, $\dot{N}d$. As usual, non arbitrage in capital market implies that households will be willing to hold the claims on firms only if their total returns match the returns to a perfectly substitutable and safe asset of size $ra \equiv rV_N lN$ (Acemoglu, 2002), therefore

$$rV_N lN + \dot{N}d = l\tilde{\pi}N + \hat{p}(1-l)^{\beta} N^{\beta} M^{1-\beta} {L_N}^{\beta} - w_N L_N - M \qquad (2.25)$$

Since we are carrying out a balanced growth path analysis, capital gains (losses) are null, $\dot{V}_N = 0 = \dot{V}_{R\&D}$. Therefore, using eq.(2.25), the households' budget constraint changes as follows

$$C + V_N \dot{N} = w_Y L_Y + w_N L_N + l\tilde{\pi}N + \hat{p}(1-l)^{\beta} N^{\beta} M^{1-\beta} {L_N}^{\beta} - w_N L_N - M$$

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Recall eq.(2.10) and use it inside $w_Y L_Y$, we get $w_Y L_Y = (1-\alpha)Y$,and free entry in intermediate good production gives $V_N \dot{N} = \hat{p}(1-l)^\beta N^\beta M^{1-\beta} {L_N}^\beta$. Then, using the equilibrium expressions for $\tilde{\pi}$ and Y, we get the economy-wide resource constraint

$$C + M + lNx = Y$$

2.8 Appendix B: The Planner Problem

The planner maximizes the utility of the representative household taking into consideration the economy-wide resource constraint and the law of motion for the state variables:

$$\max_{C,x,M,L_N} \int_0^\infty \left(\frac{C^{1-\sigma} - 1}{1-\sigma} \right) e^{-\rho t} dt,$$

$$\begin{aligned}
s.t.\ q &= \frac{1}{\eta} \frac{M}{\dot{N}} \\
\dot{N} &= \frac{(1-l)^\beta}{\eta^{1-\beta}} N^\beta M^{1-\beta} {L_N}^\beta \\
Y &= C + lNx + M \\
Y &= \left(\frac{Q}{NL_N} \right)^{1-\alpha} lNx^\alpha (\bar{L} - L_N)^{1-\alpha} \\
\bar{L} &= L_Y - L_N \\
& N_0
\end{aligned}$$

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We write the current value Hamiltonian for this problem as

$$
\begin{aligned}
H &= \frac{C^{1-\sigma}-1}{1-\sigma} + \mu\frac{(1-l)^{\beta}}{\eta^{1-\beta}}N^{\beta}M^{1-\beta}{L_N}^{\beta} \\
&\quad +\lambda\left[\left(\frac{M^{\beta}}{N^{\beta}L_N^{1+\beta}}\right)^{1-\alpha}\frac{l}{\left[(1-l)^{\beta}\eta^{\beta}\right]^{1-\alpha}}Nx^{\alpha}(\bar{L}-L_N)^{1-\alpha}-C-lNx-M\right]
\end{aligned}
$$

The relevant FOCs for this problem are

$$
C^{-\sigma} = \lambda \tag{2.26}
$$

$$
\frac{\alpha^{\frac{1}{1-\alpha}}}{\left[(1-l)^{\beta}\eta^{\beta}\right]}\left(\frac{M}{N}\right)^{\beta}\frac{(\bar{L}-L_N)}{L_N^{1+\beta}} = x \tag{2.27}
$$

$$
\lambda\frac{l(1-\alpha)\alpha^{\frac{\alpha}{1-\alpha}}}{(1-l)^{\beta}\eta^{\beta}}\left(\frac{M}{N}\right)^{\beta}\left[1+(1+\beta)\left(\frac{\bar{L}-L_N}{L_N}\right)\right]L_N^{-\beta} = \mu\frac{\beta(1-l)^{\beta}}{\eta^{1-\beta}}\left(\frac{M}{N}\right)^{1-\beta}L_N^{\beta} \tag{2.28}
$$

$$
\lambda\left[1-\frac{\beta(1-\alpha)l\alpha^{\frac{\alpha}{1-\alpha}}}{(1-l)^{\beta}\eta^{\beta}}\left(\frac{\bar{L}-L_N}{L_N}\right)\left(\frac{M}{N}\right)^{\beta-1}L_N^{-\beta}\right] = \mu\frac{(1-\beta)(1-l)^{\beta}}{\eta^{1-\beta}}\left(\frac{M}{N}\right)^{-\beta}L_N^{\beta} \tag{2.29}
$$

$$
\frac{\beta(1-l)^{\beta}}{\eta^{1-\beta}}\left(\frac{M}{N}\right)^{1-\beta}L_N^{\beta}+\frac{\lambda}{\mu}\frac{(1-\beta)\,(1-\alpha)l\alpha^{\frac{1}{1-\alpha}}}{\alpha\left[(1-l)^{\beta}\eta^{\beta}\right]}\left(\frac{M}{N}\right)^{\beta}\frac{(\bar{L}-L_N)}{L_N^{1+\beta}} = -\frac{\dot{\mu}}{\mu}+\rho \tag{2.30}
$$

Where eq.(2.28), and eq.(2.29) have been determined using eq.(2.27). Now, along the BGP all variables grow at the same constant rate; this feature, together with eq.(2.26) and eq.(2.28)

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implies $\gamma_{SP} = \frac{\dot{C}}{C} = -\frac{1}{\sigma}\frac{\dot{\lambda}}{\lambda}$. Then, setting eq.(2.28) equal to eq.(2.29) we get that

$$\left(\frac{M}{N}\right)^{1-\beta} L_N^{\beta} = \frac{(1-\alpha)l\alpha^{\frac{\alpha}{1-\alpha}}}{\beta(1-l)^{\beta}\eta^{\beta}}\left[1-\beta+\left(\frac{\bar{L}-L_N}{L_N}\right)\right]$$

This result together with the fact that all shadow values grow at the same rate which equals $-\sigma\gamma_{SP}$ can be used inside eq.(2.30) to find the equilibrium value for $\left(\frac{\bar{L}-L_N}{L_N}\right)$, which is given by the following expression

$$\frac{(1-\alpha)l\alpha^{\frac{\alpha}{1-\alpha}}}{\beta\eta\rho}\left[1-\beta+\left(\frac{\bar{L}-L_N}{L_N}\right)\right]\left\{[2\beta-\sigma(1+\beta)]\left(\frac{\bar{L}-L_N}{L_N}\right)+\beta-\sigma\right\} = (1+\beta)\left(\frac{\bar{L}-L_N}{L_N}\right)+1.$$

Solution of this second degree equation in $\chi = \frac{\bar{L}-L_N}{L_N}$ shows that there is a unique positive solution for χ and that this value differs from the solution determined in the decentralized setting. In fact, we define $\zeta_1 = \frac{(1-\alpha)l\alpha^{\frac{\alpha}{1-\alpha}}}{\beta\eta\rho}$, $\zeta_2 = 2\beta-\sigma(1+\beta)$ and we rewrite the equation accordingly

$$\zeta_1\zeta_2(1-\beta)\chi+\zeta_1\zeta_2\chi^2+[\zeta_2\zeta_1(1-\beta)+\zeta_1(\beta-\sigma)-1-\beta]\chi-1+\zeta_1(\beta-\sigma)(1-\beta)=0$$

where, for the transversality conditions to hold, we have $-1+\zeta_1(\beta-\sigma)(1-\beta)<0$. So,

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solutions are given by

$$\begin{aligned}
\chi_1 &= \frac{-\left[\zeta_2\zeta_1(1-\beta)+\zeta_1(\beta-\sigma)-1-\beta\right]}{2\zeta_1\zeta_2}+ \\
&\quad \frac{\sqrt{\left[\zeta_2\zeta_1(1-\beta)+\zeta_1(\beta-\sigma)-1-\beta\right]^2+4\zeta_1\zeta_2\left[1-\zeta_1(\beta-\sigma)(1-\beta)\right]}}{2\zeta_1\zeta_2} \\
\chi_2 &= \frac{-\left[\zeta_2\zeta_1(1-\beta)+\zeta_1(\beta-\sigma)-1-\beta\right]}{2\zeta_1\zeta_2} \\
&\quad \frac{-\sqrt{\left[\zeta_2\zeta_1(1-\beta)+\zeta_1(\beta-\sigma)-1-\beta\right]^2+4\zeta_1\zeta_2\left[1-\zeta_1(\beta-\sigma)(1-\beta)\right]}}{2\zeta_1\zeta_2}
\end{aligned}$$

and, clearly, only $\chi_1 > 0$. Moreover, comparison of χ_1 with the decentralized allocation shows that they differ.

2.9 Appendix C: Proofs of Lemmas and Propositions

2.9.1 Proof of Proposition 1

Eq.(2.1) shows that, as long as $\frac{\dot{Q}}{Q} = \frac{\dot{N}}{N}$, then $\frac{\dot{Y}}{Y} = \frac{\dot{N}}{N}$ is also true. Then, we need to show that also consumption grows at the same rate. We take the economy-wide resource constraint, given by

$$Y = C + M + lNx, \tag{2.31}$$

We take the derivative with respect to time of eq.(2.31) and recalling that, for $\frac{\dot{Q}}{Q}$ to be constant along the BGP, we need M to grow at the same rate as Q and N, we see that $\frac{\dot{C}}{C} = \frac{\dot{Y}}{Y}$. Therefore, as long as all R&D stocks grow at the same rate, all the variables in the economy grow at the same rate, given by $\frac{\dot{N}}{N} = \frac{(1-l)^{\beta}}{\eta^{1-\beta}}\left(\frac{M}{N}\right)^{1-\beta} {L_N}^{\beta}$.

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2.10 Appendix D: Social Planner in Learning-by-Doing

The planner maximizes the utility of the representative household taking into consideration the economy-wide resource constraint and the law of motion for the state variables:

$$\max_{C,x,M,L_N} \int_0^\infty \left(\frac{C^{1-\sigma}-1}{1-\sigma}\right) e^{-\rho t} dt,$$

$$\begin{aligned}
s.t.\ q &= \frac{1}{\eta}\frac{M}{\dot{N}} \\
\dot{N} &= \frac{1}{\eta^\delta} M {L_N}^{1-\delta} \\
Y &= C + lNx + M \\
Y &= \left(\frac{Q}{NL_N}\right)^{1-\alpha} lNx^\alpha(\bar{L}-L_N)^{1-\alpha} \\
\bar{L} &= L_Y - L_N \\
& \quad N_0
\end{aligned}$$

We write the current value Hamiltonian for this problem as

$$\begin{aligned}
H &= \frac{C^{1-\sigma}-1}{1-\sigma} + \mu\frac{1}{\eta^\delta} M {L_N}^{1-\delta} \\
&\quad + \lambda\left[\left(\frac{\eta^\delta}{L_N^{2-\delta}}\right)^{1-\alpha} lNx^\alpha(\bar{L}-L_N)^{1-\alpha} - C - lNx - M\right]
\end{aligned}$$

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The relevant FOCs for this problem are

$$C^{-\sigma} = \lambda \tag{2.32}$$

$$\alpha^{\frac{1}{1-\alpha}}\eta^{\delta}\frac{(\bar{L}-L_N)}{L_N}{L_N}^{\delta-1} = x \tag{2.33}$$

$$\lambda\eta^{\delta(1-\alpha)}lNx^{\alpha}(1-\alpha)\left(\bar{L}-L_N\right)^{-\alpha}L_N^{(\delta-2)(1-\alpha)}\left[1+(2-\delta)\frac{\left(\bar{L}-L_N\right)}{L_N}\right] = \mu\left(1-\delta\right)ML_N^{-\delta} \tag{2.34}$$

$$\lambda = \frac{\mu}{\eta^{\delta}}{L_N}^{1-\delta} \tag{2.35}$$

$$\frac{\lambda}{\mu}\left[\left(\eta^{\delta}{L_N}^{\delta-2}\right)^{1-\alpha}lx^{\alpha}(\bar{L}-L_N)^{1-\alpha}-lx\right] = -\frac{\dot{\mu}}{\mu}+\rho \tag{2.36}$$

Using eq.(2.33) and eq.(2.35) inside eq.(2.34) and eq.(2.36), we get

$$\frac{l\eta^{\delta}\alpha^{\frac{\alpha}{1-\alpha}}(1-\alpha)}{(1-\delta)}L_N^{\delta-1}\left[1+(2-\delta)\frac{\left(\bar{L}-L_N\right)}{L_N}\right] = \frac{M}{N} \tag{2.37}$$

$$\frac{(1-\alpha)l\alpha^{\frac{1}{1-\alpha}}}{\alpha}\frac{(\bar{L}-L_N)}{L_N} = -\frac{\dot{\mu}}{\mu}+\rho \tag{2.38}$$

Then, as eq.(2.35) shows, the economy is characterized by a unique BGP. So, $-\frac{\dot{\mu}}{\mu} = \sigma\gamma_{SPlearning} = \frac{\sigma}{\eta^{\delta}}\frac{M}{N}{L_N}^{1-\delta}$. Using this result in eq.(2.38) we get that

$$\frac{\eta^{\delta}}{\sigma}L_N^{\delta-1}\left[\frac{l\alpha^{\frac{1}{1-\alpha}}(1-\alpha)}{\alpha}\frac{\left(\bar{L}-L_N\right)}{L_N}-\rho\right] = \frac{M}{N},$$

which we set equal to eq.(2.35) to determine the equilibrium expression for labour allocation

$$\frac{\bar{L}-L_N}{L_N}=\frac{l\alpha^{\frac{1}{1-\alpha}}(1-\alpha)\sigma+\rho(1-\delta)}{l\alpha^{\frac{1}{1-\alpha}}(1-\alpha)\sigma\left[1-\delta-\sigma\left(2-\delta\right)\right]},$$

that is clearly greater than 1[7].

$$\gamma_{SPlearning}=\frac{1}{(1-\delta)}\left\{\frac{l\alpha^{\frac{\alpha}{1-\alpha}}(1-\alpha)\sigma\left[1-\delta+(1-\sigma)(2-\delta)\right]-(1-\delta)\rho}{\sigma\left[1-\delta-(2-\delta)\sigma\right]}\right\}$$

[7] We need to assume $\sigma<\frac{1-\delta}{2-\delta}$ to have $\frac{\bar{L}-L_N}{L_N}>0$

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CHAPTER 3

MULTI-STAGE RESEARCH PROCESSES IN A MULTI-INDUSTRY ECONOMY

3.1 Introduction

In Chapter 2 we have developed a model to analyze the consequences of introducing the widely-acknowledged multi-stage R&D process performed by some firms in a growing economy. We have determined interesting results, both with respect to the specific features of each R&D components and the R&D technologies and with respect to spillovers associated to basic research.

However, facts about R&D highlight an important feature that we have neglected in the previous chapter. US data show that the R&D process performed changes depending on the industry considered (*i.a.* Audretsch *et. al*, 2002) Therefore, we can group industries in two groups depending on the R&D process they carry on.

To address our question, we consider an economy with two R&D sectors, each one referring to a specific industry. The two sectors differ in the relative intensity in basic research, which, in turn, generates differences in R&D technology. The R&D sector performing basic research is modelled as in Chapter 2. The other R&D sector, which just performs development, is modelled as a typical single step R&D process.

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Being the set up a multi-industry environment, we can encompass also empirical evidence about R&D spillovers: basic research externalities are significant both inter-industry and intra-industry, whereas development spillovers are weak and cannot cross either industry borders or within industry-sectors (Funk, 2002; Jaffe, 1996).

The first major result of this broader framework is that, as in the previous chapter, we get the absence of the so-called "scale effect" in the basic-research-intensive industry. Therefore, if labour endowment of this industry changes, the growth rate of the economy is unaffected. Nonetheless, we keep the scale effect in the development-intensive industry.

However, other results change significantly. These changes are due to inter-sector spillovers from basic research and to the linkages between the two industries, channelling other spillovers. In the single industry set up, the effects of basic research spillovers on the rate of return and, as a consequence, on growth are indirect as they go through labour allocation. In this wider set up, basic research spillovers keep the indirect carrier given by labour allocation, but they both add another indirect carrier through prices and a direct one via inter-industry spillovers. So, we can conclude that the introduction of more industries besides aiming at providing a better fit to data, but entails important consequences on the outcomes of the economy.

Indeed, the effects of certain values change considerably in the multi-industry set up.

First, with respect to economically unexploitable designs from the basic-research-intensive R&D sector, we get two opposite influences in equilibrium. There is a positive effects from the spillovers they exerts on R&D productivity in their own sector and a negative effect on private incentive to invest in research from the possibility that a basic research investment

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may proof to be economically useless. Overall, we find that, as long as the probability of economic exploitation is low, an increase in the probability benefits growth, as the increase in the incentive to entry prevails, whereas for higher starting values for the probability, the same increase damages growth as the higher R&D cost offsets the positive increase in expected profits.

Then, we also find uncommon influence from R&D productivities. Productivity of basic research has two opposite effects: a direct positive effect by reducing blueprint cost and an indirect negative effect through R&D spillovers -the increase in the willingness to enter makes the number of innovators in the basic-research-intensive sector increase, thus reducing the ration of basic research over applied knowledge. This implies a lower equilibrium level for basic research spillovers, both intra and inter industry and this affects negatively growth. Similarly, productivity of development in the multi-stage R&D process exerts a negative effect on growth, again due to its influence on R&D externalities. It is worth recalling that in the single industry set up these effects are null. Differences are due to inter-industrly linkages and inter-industry spillovers: one of them is enough to change the influence of these parameters.

Finally, productivity of development in the development-intensive industry has a negative effect on growth, a result due to inter-industry effects. The increase in entry in the development-intensive sector caused by an increase in its R&D productivity shifts away resources R&D in the other industry. Thus, spillovers shirk.

Moreover, the introduction of inter and intra industry spillovers associated to basic

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research adds some new elements which may lead to market failure. Therefore, the decentralized equilibrium fails to be Pareto optimal and the optimal fiscal policy contains new tools to address the specific distortions added by basic research when industries are different and linked.

Obviously, the richer menu of fiscal tools contains instruments accounting for both inter and intra spillovers. Nonetheless, it also embodies instruments needed to account for intra-industry spillovers that manage to propagate across industries through price relationships.

In this wider set up, we keep the main result about basic research subsidization and we add another fiscal advice with respect to R&D: R&D in the industry neglecting basic research must be taxed, to increase the relative R&D cost to perform development only.

A multi-industry set up can be easily adapted to be suitable to describe a multi-country world. To this respect, empirical evidence points out big differences in innovation patterns: few developed countries account for the majority of R&D investment. Also privately-performed basic research is concentrated in these countries. Developing countries prefer imitating developed countries knowledge. The final part of the chapter deals with this issue and technological leadership determined when basic research, multi-stage R&D and R&D spillovers are embedded in the economy The resulting outcomes differ to the patterns determined when R&D is treated as homogeneous and inter and intra-sector spillovers are mainly neglected. Countries performing basic research never switch to technological followers. Basic research, through its spillover effects grants permanence in technological leadership, a feature widely aknowledged in policy making (PCAST, 2002).

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The Chapter is organized as follows: Section 2 describes the economy, presents the model and analyzes the decentralized equilibrium. Section 3 introduces the Social Planner problems and discusses some welfare considerations. Section 4 concludes.

3.2 The Economy

We distinguish basic-research-intensive activities from development-intensive ones along the lines presented in the introductory chapter and formalized in Chapter 2: these distinguishing features modify both the structure of payoffs from R&D efforts and the structure of the research process with respect to standard horizontal innovation literature.

Differently from Chapter 2, here the economy is characterized by two R&D sectors, that differs in terms of the type of research activity they perform: sector D is development-intensive, sector R is basic-research-intensive. Each R&D sector produces designs which are necessary to enter production of the industry specific intermediate goods, which are, in turn, sector-specific inputs in the production of each industry final good. Then, the two final goods are aggregated and the resulting good is used for consumption, input in the production of intermediate goods and input in the preliminary research processes[1].

Consistently to the definition of development activity given in the introductory chapter, we assume that in the D sector there is a unique R&D activity, which delivers only designs that translate into new varieties with certainty, but subject to erosion of monopoly power. Analogously, in the R sector the R&D process consists of two steps as in Chapter 2. To

[1] In the R sector, the preliminary research process is the basic research stage. Obviously, in the D sector, the preliminary research process coincide with the unique research process carried on.

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account for the lower innovation content of development-intensive designs, we argue that they are subject to imitation and close substitutes. We model this feature introducing erosion of monopoly payoffs from innovating in industry D. We keep the standard assumption that each variety, once introduced, will be used in the final good sector forever (Romer, 1991; Acemoglu, 2002).

The structure of the economy is summarized in Figure 3.1[2].

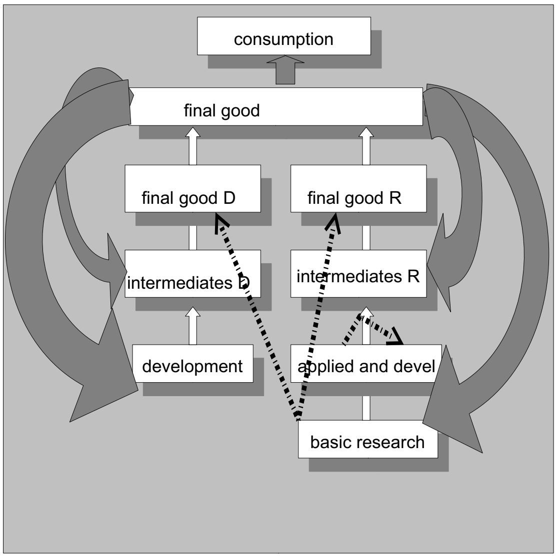

Figure 3.1. Structure of the Economy

3.2.1 Set up

There are three types of agents in the model. Households maximize utility subject to their budget constraint. They enjoy both labour and asset income and decide whether to consume or invest. In each industry, final good producers hire industry-specific labour and

[2]Upward pointing white arrows show the sequence of processes needed to produce final output in sector D and R respectively. Gray arrows highlight the different purposes of final output. Dotted arrows show the direction of externalities.

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intermediate goods and combine them to produce a final good, which is sold to aggregating firms to create a unique final good sold at unit price. This final good, as seen in Figure 3.1, serves different purposes: consumption, input for intermediate good production and input for the first stage of R&D in both industries. Applied research in the R sector produces designs using only basic research and industry-specific-labour as costly inputs.

R&D firms devote resources to discover new designs. Depending on the sector, both the processes of creating new designs and the economic characteristics of the designs are different. In the D sector, only development intensive patents are produced; these designs are created using a single technology and they are always economically exploitable. In the R sector, only basic-research-intensive designs are created through a two steps process, each step being associated to a specific technology: basic research ideas are created, and then they are given to another technology which tries to transform them into new exploitable designs. With a given probability, exploitability of the final design coming from the manipulation of basic research ideas may be zero. This assumption is consistent to the literature, since we are accounting for the fact that fundamental discoveries which are realized without any specific economic aim may fail to be useful to create a new product or process. However, we assume that entry in the sector obliges firms to go through all the research stages before knowing whether their investment leads to a positive payoff or not. In this way we take into account that basic research ideas alone are not enough to predict their potential economic value.

Firms choose which sector to enter, knowing in advance the characteristics of each sector.

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All designs and ideas are patented. We keep the standard assumption about perpetual patent: once a design has been patented, the owner of the patent holds the exclusive and perpetual right about its potential economical exploitation. However, perpetual patents do not couple with perpetual monopolistic profits anymore. In fact, here not all the designs allow for intermediate goods and not all intermediate goods remain monopolized forever.

In the introduction, we have argued that breakthrough innovations, which are mainly delivered by basic research, are more likely to generate high and long-lasting profits than development intensive designs and that this difference is due to differences in the innovative content rather than to the patent system. An easy way to account for this feature is to modify the payoff structure from entering the intermediate good sector in each industry. To this respect, we assume that owners of development intensive designs (entrants in the D sector) produce intermediate goods which transform from monopolized to competitive with a given probability, namely erosion of monopoly power (Barro and Sala-I-Martin, 2004), while the owners of basic research intensive designs which turn out to be economically exploitable (entrants in the R sector) produce intermediate goods which are monopolized forever[3]. In this way, we account both for close substitution which affects development intensive designs and for the high payoffs spurring from breakthrough innovations. Note that we are assuming that no breakthrough innovation may ever be produced by development activity and that each basic research design which is economically exploitable is a breakthrough innovation. Obviously, reality delivers a more complicated picture, since development activity has generated some breakthrough innovation and basic research has produced some design which has

[3]Owners of basic research idea which transform into economically useless designs simply do not produce.

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incurred in close substitute in the short-medium run. Anyway, as the literature identifies basic research as the major source for breakthrough innovations and development as the activity whose relatively low level of breakthrough-ness does not guarantee "to be in business for the long haul", then our assumption seems quite reasonable.

3.2.2 The Model

The new elements which we want to introduce in a standard two-R&D-sector horizontal innovation model, can be summarized in the following key assumptions: *(i)* sector D designs are always economically exploitable and affected by erosion of monopoly power, *(ii)* basic research is the preliminary step for the production of breakthrough innovations in the R sector; *(iii)* a final R design may be economically useless; *(iv)* basic research generates inter-sector and intra-sector spillovers on productivity. We will use these assumptions to build the model.

Final good sector. Producers of final good have access to a production technology which combines a number of intermediate inputs to produce final output, which is then sold in the market at unit price. Formally,

$$Y = Y_D^{1-\psi} Y_R^{\psi}, \tag{3.1}$$

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where

$$
\begin{aligned}
Y_D &= E_D^{1-\alpha}\left(\int_0^{N_D-N_{DC}} x_{jDMon}^{\alpha}dj + \int_0^{N_{DC}} x_{iC}^{\alpha}di\right)\bar{L}_D^{1-\alpha}, &(3.2)\\
Y_R &= E_R^{1-\alpha}\left(\int_0^{lN_R} x_{jRMon}^{\alpha}dj\right)L_{YR}^{1-\alpha} &(3.3)
\end{aligned}
$$

$0 < \psi < 1$, $0 < \alpha < 1$. First, note that the final good sector aggregates in a Cobb-Douglas fashion two goods, Y_D and Y_R, that belongs to the two sectors characterizing the economy: sector D and sector R. Y_D and Y_R are produced combining sector-specific intermediate goods and sector-specific labour, $\bar{L}_D$ in industry D and L_{YR} for industry R. In industry D labour is entirely devoted to final good production, whereas in industry R labour is used both for final good production and for R&D. Assuming industry-specific labour input is undoubtedly a strong assumption, that we adopt claiming that workforce able to work with basic research intensive innovations must be more skilled than workforce dealing with other innovations[4].

x_{jhMon}, $h = D, R$, is the employment of the jth type of monopolized intermediate good in sector h and x_{iC} is the employment of the ith type of competitive intermediate good. Competitive intermediate goods are used in sector D only, where monopolized goods turn competitive as a consequence of the high probability of close substitutes due to the low level of breakthrough innovations. N_D is the total number of varieties of intermediates in sector D, no matter whether monopolized or competitive and lN_R is the total number of varieties of intermediates in sector R. Since we assume erosion of monopoly power in sector D, N_{DC}, is the stock of development patents which have been surrounded by close substitutes in sector

[4]for a similar tratement for industry specific labour see Acemoglu (2002)

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D.

In sector D, the number of varieties of intermediates at a point in time, N_D, corresponds to the size of the stock of designs at the same point in time. In sector R things are more complicated. lN_R gives the number of varieties of intermediate goods at a point in time, which obviously corresponds to the size of economically exploitable designs. However, lN_R does not corresponds to the total stock of designs produced in sector R, which is given by N_R. This happens because not all the designs obtained transforming basic research ideas are economically exploitable and we assume that there is a probability l, $0 < l < 1$, that a type-R final blueprint is economically exploitable. Therefore, since at each point in time, we have N_R final blueprints, if we assume that N_R is large enough, for the law of large number, we have lN_R exploitable blueprints. As an exploitable blueprint is associated to a variety of intermediate good, then we have lN_R intermediate good.

In both sectors, final good production is affected by positive R&D externalities, E_D and E_R. E_Q is given by

$$E_R = \left(\frac{Q}{N_R L_{NR}} \right). \tag{3.4}$$

E_R looks exactly as in Chapter 2. We keep our assumption about the determinants of R&D spillovers: positive contribution of basic research,negative congestion effect by patent holders. However, differently from Chapter 2 here we account also for inter-industry externality effects, recalling that R&D spillovers are higher intra-sector than inter-sector (Lichtemberg, 1990). To account for this feature, while we model E_R exactly as in the single-industry set up, E_D is a new feature introduced in this two-industry set up accounting for those

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inter-industry spillovers from basic research acknowledged by empirical analysis. We assume that inter-industry spillovers are generated only by new basic research ideas, $\dot{N}_R q$, and not by the whole inventory, Q. Moreover, it is not the whole bulk of new ideas to benefit the development-intensive industry, but just a fraction, $\xi \dot{N}_R q$. Then, we assume that the negative effect of stupid scientists matters only intra-sector, as we deal with industry-specific workforce:

$$E_D = \left(\xi \frac{\dot{N}_R q}{l N_R} \right). \tag{3.5}$$

where $0 < \xi < 1$.

Final good is used for consumption, input for the production of intermediate goods and input for creation of D designs and basic research ideas.

Since we take the price of Y as the numeraire, the following price index holds

$$1 = \left(\frac{1-\psi}{P_D} \right)^{1-\psi} \left(\frac{\psi}{P_R} \right)^{\psi}. \tag{3.6}$$

Intermediate good sector. Each sector has its specific intermediate good producers. As usual, to become an intermediate producer, you must acquire a blueprint from the R&D sector first, and a blueprint is simply the technology or know-how for transforming final goods to differentiated intermediate inputs. Differently from the previous chapter, depending on the blueprint the firm buys, its payoffs change: in the R sector, every patent allowing for a new variety grants perpetual monopolistic profits to producer; in the D sector, a patent cannot grant the same payoff, due to the lower level of innovation in the research sector: If

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close substitutes arise, then profits drop to the competitive level. However, also buying a patent in the R sector does not guarantee positive payoffs with certainty, since the patent may turn out to be unexploitable to produce a new intermediate good.

We assume that an intermediate good no matter its type and sector, once invented, costs one unit of Y to produce and, as eq.(3.2) and eq.(3.3) show, it is used in the production of final good forever.

Research firms. In sector D, at a point in time, the technology exists to produce N_D varieties of intermediate goods. In sector R, at a point in time, the technology exists to produce lN_R varieties of intermediate goods. An expansion of the number of variety requires a technological advance in the sense of an invention allowing for the production of a new type of intermediate good. A key assumption in horizontal innovation framework is that this technological advance requires purposive effort in the form of R&D.

The R&D sector is competitive. Researchers produce blueprints for producing a new variety of differentiated intermediate goods. Blueprints are protected by perpetual patents. Innovators auction their blueprints to a large number of potential buyers, thus absorbing all the profits of the intermediate good sector.

Depending on the sector chosen for entry, payoffs from entry change, along the lines described above. Sector D grants a new exploitable design with certainty, but it entails the negative perspective of future erosion of monopoly power. Sector R, instead, gives patents that may be economically useless, but unaffected by the possibility of eroded monopolistic profits.

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In this framework, once a firm has chosen the sector to enter, the type of blueprint is not uncertain with respect to its type. Uncertainty exists with respect to the economic exploitation of designs in the R sector and about duration of monopoly power in the D sector.

We summarize the structure of the entry game in Figure 3.2.

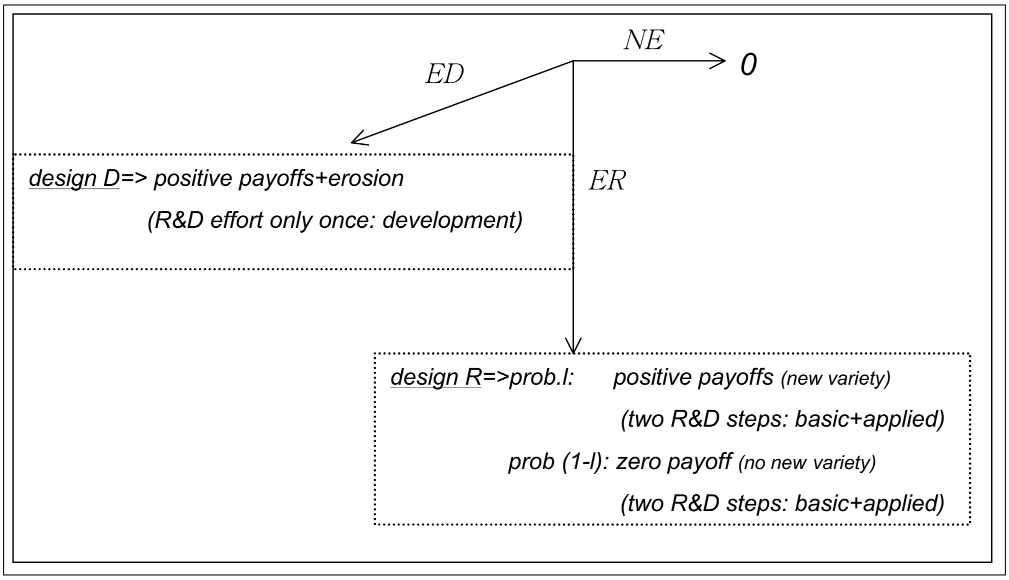

Figure 3.2: The Entry Game

Where ED stands for entry in the D sector, ER for entry in the R sector and NE for no entry.

No matter the sector of entry, firms face the two stage decision process typical of standard models of horizontal innovation. First, they decide whether to enter or not and if they enter, they also choose the sector. Entrants will buy a patent for a new variety of good if the market value of the firm producing the new variety of intermediate good is at least as large as the R&D cost they have to bear to start the firm. Then, they decide the optimal price at

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which to sell their new intermediate goods to final good sector firms. This price determines the demand they face and, as a consequence, the expected future profits. We solve the two stage problem backward. Since we assume that there is free entry into the business of being an inventor, we will deal with a free entry condition that holds in equilibrium such that entry occurs when the market value of the firm equals the R&D cost. The market value of a new intermediate good firm in sector h, $h = D, R$, is given by $V_h = \int_t^{\infty} e^{-\int_t^s r(\tau)d\tau} E_t \pi_h(s) ds$,where π_h are the instantaneous profits from intermediate good production in sector h and E_t is the expectation operator, conditional on information at time t. Expected profits at time s as seen from time t from entry in the D sector are given by $E_t \pi_D(s) = \pi_{DMon}(s) e^{-p(s-t)}$, where p is the parameter governing the Poisson process which we assume to govern erosion of monopoly power. If entry occurs in the R sector, then an exploitable design granting perpetual monopolistic profits, π_{RMon}, happens with probability $l, 0 < l < 1$. Therefore, for the R sector we have that $E_t \pi_R(s) = l \pi_{RMon}$.

In both sectors, an intermediate good costs one unit of Y to produce, therefore, profits accruing to firm producing variety j in sector h are given by $\pi_{jh} = (\tilde{p}_{jh} - 1) x_{jh}$, $h = D, R$, where $\tilde{p}_{jh}$ is determined by profit maximization in the final good sector. The market values for a new intermediate good firm in sector D and R respectively are given by

$$V_D = \frac{\pi_{DMon}}{r + p}, \tag{3.7}$$

$$V_R = l \left(\frac{\pi_{RMon}}{r} \right) \tag{3.8}$$

For the D sector, we argue that investors care only about eq.(3.7) and that it is consistent

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with individual risk aversion, because we assume that uncertainty is purely idiosyncratic (Barro and Sala-I-Martin, 2004; Groth 2004). This implies that the stochastic event that a firm looses its monopoly power is not correlated with other firms loosing their monopolistic position and the stochastic event that a firm gets a design of a given type is not correlated with the type of designs of other firms. As a consequence of idiosyncratic uncertainty, share owners can eliminate the risk by diversifying their portfolio across many different firms and expected future profits are still discounted by the safe rate, r.

In both sectors, we assume a sector specific R&D cost determined by R&D firms profit maximization problems in each sector. The R&D cost that entrants must pay corresponds to the price of a new patent.

In sector D, the representative firm produce a new blueprint according to $b_{Di} = \frac{1}{\eta_D} M_{Di}$, where b_{Di} is a single new blueprint. Since there are $\dot{N}_D$ identical innovators, the speed of new ideas creation is given by

$$\dot{N}_D = \frac{1}{\eta_D} M_D, \tag{3.9}$$

where η_D is an exogenous productivity parameter and M_D is the amount of final output devoted to design production in the sector.

In the R sector, we consider the two-step process for new design creation. Each firm i must undertake firm's specific basic research according to the following technology

$$q_i = \frac{1}{\eta_Q} M_{Qi}, \tag{3.10}$$

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where η_Q is an exogenous productivity parameter and M_{Qi} is the amount of final output used by firm i in basic research production. Then, basic research output, q_i is used in another research activity within the same R&D firm, which transforms it in attempt to produce a new exploitable design according to

$$b_{Ri} = (1-l)^{\beta} (NL_{NRi})^{\beta} q_i^{1-\beta} \tag{3.11}$$

where b_{Ri} corresponds to a single new blueprint. At the aggregate level there are $\dot{N}_R$ identical innovators, therefore eq.(3.10) and (3.11) and a symmetry assumption show that new development designs in the basic-research-intensive industry evolve according to

$$\dot{N}_R = \frac{(1-l)^{\beta}}{\eta_Q^{1-\beta}} (NL_{NR})^{\beta} M_Q^{1-\beta}. \tag{3.12}$$

As eq.(3.12) shows, final designs accumulate thanks to basic research ideas and labour, L_{NR}. Then there is a positive externality given by the stock of useless final designs produced in the sector, $(1-l)^{\beta} N_R^{\beta}$

Households. Households maximize utility over an infinite horizon. They are endowed with constant aggregate flow of R-sector-specific labour, $\bar{L}_R = L_{YR} + L_{NR}$ and D-sector-specific labour, $\bar{L}_D$. Both inputs are supplied inelastically. Their objective function is given by

$$U(C) = \int_0^{\infty} \left(\frac{C^{1-\sigma} - 1}{1-\sigma} \right) e^{-\rho t} dt$$

Households receive the wage rate on fixed aggregate quantities of sector-specific labour and

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enjoy assets return as well. They discount the future at rate ρ. Their budget constraint is given by

$$C + \dot{a} = w_D \bar{L}_D + w_{YR} L_{YR} + w_{NR} L_{NR} + ra$$

where a denotes assets. The consumption plan they set when maximizing utility subject to the constraints satisfies standard Euler equation

$$\frac{\dot{C}}{C} = \frac{1}{\sigma}(r - \rho) \tag{3.13}$$

3.2.3 Decentralized Equilibrium and BGP without Erosion of Monopoly Power

3.2.3.1 BGP

Proposition 3.1 As long as development activities grow at the same rate, that is $\frac{\dot{N}_R}{N_R} = \frac{\dot{N}_D}{N_D}$, then all variables in the economy will grow at the same rate, given by

$$\frac{\dot{N}_R}{N_R} = \frac{(1-l)^{\beta}}{\eta_Q^{1-\beta}} L_{NR}^{\beta} \left(\frac{M_Q}{N_R} \right)^{1-\beta} \tag{3.14}$$

Proof. Eq.(3.1)-(3.3) show that $\frac{\dot{Y}_D}{Y_D} = \frac{\dot{N}_D}{N_D}, \frac{\dot{Y}_R}{Y_R} = \frac{\dot{N}_R}{N_R}$ and, as a consequence, $\frac{\dot{Y}}{Y} = \beta \frac{\dot{N}_D}{N_D} + (1-\beta)\frac{\dot{N}_R}{N_R}$. Thus, if $\frac{\dot{N}_R}{N_R} = \frac{\dot{N}_D}{N_D}$, we have that

$$\gamma_Y = \gamma_{Y_D} = \gamma_{Y_R} = \gamma_{N_D} = \gamma_{N_R}.$$

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Then, we need to show that also consumption grows at the same rate. We take the economy-wide resource constraint[5], given by

$$Y = C + M_D + M_Q + N_D x_{DMon} + lN_R x_{RMon}, \tag{3.15}$$

where, since we ruling out erosion of monopoly power, we have set $N_{DC} = 0 = x_{DC}$. We take the derivative with respect to time of eq.(3.15) and recalling that for $\frac{\dot{N}_D}{N_D}$, $\frac{\dot{N}_R}{N_R}$ and $\frac{\dot{Q}}{Q}$ to be constant along the BGP we need M_D to grow at the same rate as N_D and M_Q to grow at the same rate as N_R, we see that if $\frac{\dot{N}_R}{N_R} = \frac{\dot{N}_D}{N_D}$, then $\frac{\dot{Q}}{Q} = \frac{\dot{N}_R}{N_R}$ and $\frac{\dot{C}}{C} = \frac{\dot{Y}}{Y}$. Therefore, as long as stocks of applied knowledge grow at the same rate, all the variables in the economy grow at the same rate, given by $\frac{\dot{N}_R}{N_R} = \frac{(1-l)^{\beta}}{\eta_Q^{1-\beta}} L_{NR}^{\beta} \left(\frac{M_Q}{N_R}\right)^{1-\beta}$. ■

3.2.3.2 Decentralized Equilibrium

Profits from final good production are given by

$$Y_D^{1-\psi} Y_R^{\psi} - P_R Y_R - P_D Y_D,$$

where P_h, $h = R, D$, is the price of final good produced in sector h. The price of final output, Y, is taken as the numeraire. Final good production is competitive, therefore, profit maximization implies that $P_D = (1-\psi) Y_R^{\psi} Y_D^{-\psi}$, $P_R = \psi Y_R^{\psi-1} Y_D^{1-\psi}$ and $\frac{P_R}{P_D} = \frac{\psi}{(1-\psi)} \frac{Y_D}{Y_R}$. In each sector, firms producing the sector specific final good face the following maximization

[5] See Appendix A

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problem in sector D and R respectively

$$\max_{\{x_{DMon}\}_{j=0}^{N_D},\bar{L}_D} \left[P_D E_D^{1-\alpha}\left(\int_0^{N_D} x_{jDMon}^{\alpha} dj\right)\bar{L}_D^{1-\alpha} - w_D\bar{L}_D - \int_0^{N_D}\tilde{p}_{jDMon}x_{jDMon}dj\right]$$
$$\max_{\{x_R\}_{j=0}^{lN_R},L_{YR}} \left[P_R E_R^{1-\alpha}\left(\int_0^{lN_R} x_{jRMon}^{\alpha} dj\right)\left(\bar{L}_R - L_{NR}\right)^{1-\alpha} - w_R\left(\bar{L}_R - L_{NR}\right) - \int_0^{lN_R}\tilde{p}_{jRMon}x_{jRMon}dj\right]$$

$w_h, h = R, D$, is the wage rate for the sector-specific labour input, $\tilde{p}_{jhMon}$, $h = R, D$, is the price of the jth monopolized intermediate good in the h sector. Final good sector is competitive, therefore input prices are taken as given. Instantaneous profit maximization gives the following first order conditions, once symmetry has been imposed

$$\tilde{p}_{DMon} = P_D E_D^{1-\alpha}\alpha x_{DMon}^{\alpha-1}\bar{L}_D^{1-\alpha} \quad (3.16)$$
$$\tilde{p}_{RMon} = P_R E_R^{1-\alpha}\alpha x_{RMon}^{\alpha-1}\left(\bar{L}_R - L_{NR}\right)^{1-\alpha}, \quad (3.17)$$
$$w_{YR} = P_R E_R^{1-\alpha} l N_R x_{RMon}^{\alpha}(1-\alpha)\left(\bar{L}_R - L_{NR}\right)^{-\alpha}, \quad (3.18)$$
$$w_D = (1-\alpha) P_D E_D^{1-\alpha} N_D x_{DMon}^{\alpha}\bar{L}_D^{-\alpha}. \quad (3.19)$$

Eq.(3.16)-(3.17) are the inverse demand functions faced by intermediate good producers. Since we assume that an intermediate good no matter its type and sector, once invented, costs one unit of Y to produce, the demand functions allow us to write the profit flows for intermediate goods. If we deal with the jth monopolized intermediate good, the profit flow is given by $\pi_{jDMon} = (\tilde{p}_{DMon} - 1)x_{jDMon}$ and $\pi_{jRMon} = (\tilde{p}_{RMon} - 1)x_{jRMon}$, where $\tilde{p}_{DMon}$ by eq.(3.16) and $\tilde{p}_{RMon}$ is given by eq.(3.17). Since monopolists set marginal revenues equal to marginal cost, we get that $\tilde{p}_{RMon} = \frac{1}{\alpha} = \tilde{p}_{DMon}$, $x_{RMon} = \alpha^{\frac{2}{1-\alpha}} P_R^{\frac{1}{1-\alpha}} E_R \left(\bar{L}_R - L_{NR}\right)$, $x_{DMon} = \alpha^{\frac{2}{1-\alpha}} P_D^{\frac{1}{1-\alpha}} E_D \bar{L}_D$. Therefore, symmetry across all the monopolized intermediate goods, together with eq.(3.4) and eq.(3.5), imply that

$$\pi_{jDMon} = \pi_{DMon} = \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} P_D^{\frac{1}{1-\alpha}} E_D \bar{L}_D, \tag{3.20}$$

$$\pi_{jRMon} = \pi_{RMon} = \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} P_R^{\frac{1}{1-\alpha}} E_R \left(\bar{L}_R - L_{NR}\right) \tag{3.21}$$

Monopolistic profits represent the positive payoffs from R&D investment, providing the right incentive to innovate. Innovation is a costly activity and the cost varies depending on the sector of entry.

In sector D, R&D firms auction their blueprints to a large number of potential buyers, thus absorbing all the profits of the intermediate good sector through the blueprint price $\hat{p}_D$ (free entry condition). Therefore,

$$V_D = \hat{p}_D \ , \tag{3.22}$$

where, according to eq.(3.7), $V_D = \frac{\pi_{DMon}}{r}$, with π_{DMon} given by eq.(3.20). Then, R&D firms are competitive and their maximization problem is given by

$$\max_{M_{Di}} \left(\frac{\hat{p}_{Di}}{\eta_D} M_{Di} - M_{Di}\right),$$

from which, using also symmetry, we derive the zero profit condition,

$$\hat{p}_D = \eta_D. \tag{3.23}$$

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Eq.(3.22) can be solved for the interest rate, and, using eq.(3.23), we get

$$r_D = \frac{\left(\frac{1-\alpha}{\alpha}\right)\alpha^{\frac{2}{1-\alpha}} P_D^{\frac{1}{1-\alpha}} E_D \bar{L}_D}{\eta_D} \tag{3.24}$$

Moreover, we use the final good price index, eq.(3.6) to substitute for P_D inside eq.(3.24) to get

$$r_D = \frac{\left(\frac{1-\alpha}{\alpha}\right)\left[\alpha^2\psi(1-\psi)^{\frac{\psi}{1-\psi}}\right]^{\frac{1}{1-\alpha}} P_R^{\frac{\psi}{(\psi-1)(1-\alpha)}} E_D \bar{L}_D}{\eta_D} \tag{3.25}$$

Also in sector R, R&D firms auction their blueprints to a large number of potential buyers, thus absorbing all the profits of the intermediate good sector through the blueprint price $\hat{p}_R$ (free entry condition). Therefore,

$$V_R = \hat{p}_R \ , \tag{3.26}$$

where, according to eq.(3.8), $V_R = \frac{l\pi_{RMon}}{r}$, with π_{RMon} given by eq.(3.21). Firms are competitive and they generate final blueprints using labour and basic research plus an externality effect played by the stock us useless final blueprints. We assume that they have to produce basic research to use it into final blueprint production. Firms pay the wage rate, w_{NR}, for each unit of industry-specific labour unit they hire and pay the unit price for final output. Shareowners receive firms' net cash flow as dividend. Firm i objective is given by

$$\max_{M_Q, L_{NR}} \hat{p}_R(1-l)^\beta N_R^\beta q_i^{1-\beta} L_{NRi}^\beta - M_{Ri} - w_{NR}L_{NRi}$$

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subject to eq.(3.10).

First order conditions, together with symmetry, imply

$$\hat{p}_R = \frac{\eta_Q^{1-\beta}}{(1-\beta)(1-l)^{\beta}} \left(\frac{M_Q}{N_R}\right)^{\beta} L_N^{-\beta}, \tag{3.27}$$

$$w_{NR} = \hat{p}_R \frac{\beta(1-l)^{\beta}}{\eta_Q^{1-\beta}} N \left(\frac{M_Q}{N_R}\right)^{1-\beta} L_{NR}^{\beta-1}. \tag{3.28}$$

In equilibrium, non arbitrage in the sector-specific labour market determines wage equality within industry. We set eq.(3.18) equal to eq.(3.28). Solving for $\hat{p}_R$ we get

$$\hat{p}_R = \frac{\eta_Q^{1-\beta} l(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}} P_R^{\frac{1}{1-\alpha}}}{\beta(1-l)^{\beta}} E_R \left(\frac{M_Q}{N_R L_{NR}}\right)^{\beta-1}. \tag{3.29}$$

If we look at eq.(3.29), we see that the same increase in E_R makes the price of a blueprint in the R industry increase. This effect is due to non arbitrage in the labour market: an increase in E_R, by enhancing the marginal productivity of labour employed in the production of Y_R, makes wage increase. Then, non arbitrage in the labour market determines a increase in wage in the R&D sector that, in turns, makes the price of a blueprint go up. We can now determine the free entry condition in industry R : recall eq.(3.26), that, using eq.(3.21) for payoffs, the interest rate as discount factor and eq.(3.29) for the entry cost we rewrite as

$$r_R = \frac{\alpha(1-l)^{\beta}}{\eta_Q^{1-\beta}} \left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right) \left(\frac{M_Q}{N_R}\right)^{1-\beta} L_{NR}^{\beta} \tag{3.30}$$

Eq.(3.29) together with eq.(3.27) constitute a system of two equations in $\hat{p}_R$, which we

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solve to find

$$P_R^{\frac{1}{1-\alpha}} = \frac{\beta}{(1-\beta)\,l(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}} \left(\frac{M_Q}{N_R L_{NR}}\right) E_R^{-1}. \tag{3.31}$$

Note that the price of R industry final good, P_R, decreases if intra-industry spillovers from basic research go up. Recalling the price index, eq.(3.6), as the price of final good in the R industry is inversely related to the price of final good in the D industry, then P_D will move in the opposite direction following the same increase from E_R. So, we have found that there is an indirect channel though which intra-sector spillovers from basic research may reach the development-intensive industry. Overall, we have that basic research spillovers can influence the other industry directly, through inter-industry externality and indirectly, through prices.

If we go back to eq.(3.29), we see that the direct positive effect played by E_R is completely cancelled by the negative effect played by E_R on P_R, as showed in eq.(3.31).

Now, we substitute eq.(3.31) inside eq.(3.25), and we assume that $\psi = \beta$[6]

$$r_D = \frac{(1-\alpha)}{\alpha\eta_D}\left[\beta(1-\beta)^{\frac{\beta}{1-\beta}}\right]^{\frac{1}{1-\alpha}} \left[\frac{(1-\beta)\,l(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}}{\beta}\right]^{\frac{\beta}{1-\beta}} \left(\frac{M_Q}{N_R L_{NR}}\right)^{\frac{\beta}{\beta-1}} E_R^{\frac{\beta}{1-\beta}} E_D \bar{L}_D \tag{3.32}$$

Finally, we use eq.(3.4) and eq.(3.5) to substitute for E_R and E_D

$$r_D = \frac{(1-\alpha)\,\eta_Q^{\beta}\xi\left[\beta(1-\beta)^{\frac{\beta}{1-\beta}}\right]^{\frac{1}{1-\alpha}}}{\alpha\eta_D l(1-l)^{\frac{\beta^2}{1-\beta}}} \left[\frac{(1-\beta)\,l(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}}{\beta}\right]^{\frac{\beta}{1-\beta}} \left(\frac{M_Q}{N_R}\right)^{1-\beta} L_{NR}^{\beta}\bar{L}_D. \tag{3.33}$$

and, as non arbitrage must hold in equilibrium, we set this expression for the rate of return

[6] this assumption is needed to reach a close-form solution

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equal to the expression for the rate of return determined by free entry in the R industry, eq.(3.30). We determine the equilibrium value for labour allocation in the R industry

$$\frac{\bar{L}_R - L_{NR}}{L_{NR}} = \frac{\eta_Q}{\eta_D}\left[\beta(1-\beta)^{\frac{\beta}{1-\beta}}\right]^{\frac{1}{1-\alpha}}\left[\frac{(1-\alpha)\,\alpha^{\frac{2\alpha}{1-\alpha}}\,(1-\beta)^{\beta}\,l^{2\beta-1}}{\beta^{\beta}(1-l)^{\beta}}\right]^{\frac{1}{1-\beta}}\xi\bar{L}_D \tag{3.34}$$

Non arbitrage implies also that $r_D = r_R = r$. Then, the fact that all variables grow at the same rate entails $\gamma = \frac{\dot{C}}{C} = \frac{1}{\sigma}(r-\rho)$, which we rewrite according to Proposition 3.1 as $r_{Savings} = \sigma\left[\frac{(1-l)^{\beta}}{\eta_Q^{1-\beta}}\left(\frac{M_Q}{N_R}\right)^{1-\beta}L_{NR}^{\beta}-\rho\right]$. By setting this expression for the interest rate equal to eq.(3.30), we get

$$\left(\frac{M_Q}{N_R}\right)^{1-\beta} = \frac{\rho\eta_Q^{1-\beta}}{(1-l)^{\beta}\left[\alpha\beta\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)-\sigma\right]}, \tag{3.35}$$

that, together with eq.(3.14) and eq.(3.34) allows to reach the equilibrium expression for the growth rate[7]

$$\gamma = \frac{\rho}{\left[\alpha\beta\frac{\eta_Q}{\eta_D}\left[\beta(1-\beta)^{\frac{\beta}{1-\beta}}\right]^{\frac{1}{1-\alpha}}\left[\frac{(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}(1-\beta)^{\beta}l^{2\beta-1}}{\beta^{\beta}(1-l)^{\beta}}\right]^{\frac{1}{1-\beta}}\xi\bar{L}_D-\sigma\right]} \tag{3.36}$$

3.2.3.3 Comparative Statics

In this chapter, we have departed from the set up developed in Chapter 2 to represent industries differing in the type of R&D performed and to tackle R&D spillovers trajecto-

[7] For the transversality condition to hold, we need $\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right) > \frac{1}{\alpha\beta}$, that, using eq.(3.34) can be rewritten as

$$\frac{\eta_Q}{\eta_D}\left[\beta(1-\beta)^{\frac{\beta}{1-\beta}}\right]^{\frac{1}{1-\alpha}}\left[\frac{(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}\,(1-\beta)^{\beta}\,l^{2\beta-1}}{\beta^{\beta}(1-l)}\right]^{\frac{1}{1-\beta}}\xi\bar{L}_D > \frac{1}{\alpha\beta}$$

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ries across the economy. So, here we have accounted for specific features distinguishing development-intensive research activity from basic-research-intensive one in a set up where both are at work. This choice has generated an equilibrium value for BGP which differs significantly both from standard results and from the equilibrium identified in the single-industry economy. This differences are due to several features of the model: inter-sector and intra-sector externalities taking place at the same time, multi-stage research process,.. Changes with respect to the single industry case are due both to multiple industries and to spillovers.

First, we deal with the probability of economic exploitability of a given research effort in the R sector affects the growth rate. This probability is exogenously given in the model and it is denoted by l. An increase in l exerts two opposite effects on the economy: it lowers the present discounted value of starting a new firm in the R sector, by increasing the R&D cost, as showed by eq.(3.30), but, at the same time, it plays other effects on returns in the other industry: through inter-sector externality, E_D, and prices, as showed by eq.(3.25), eq.(3.31) and the price index. An increase in l has a direct negative effect by increased congestion on E_D. Nonetheless, it has a positive effect, although indirect, by lowering P_R : this determines an increase in P_D, that, in turn, increases demand for intermediate goods in the D industry, thus benefitting returns. Finally, an increase in l makes E_R increase, as an increase in productivity of development in the basic-research-intensive industry reduces the ratio of basic research over applied designs. Eq.(3.36) shows that the BGP growth rate is affected by both opposite effects. For small value for l, an increase in l is good for growth

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as the positive effects exerted through spillovers overcomes the negative effects. Whereas for high values, the same increase in l damages growth. The threshold value for l is given by $l^* = \frac{1-2\beta}{(1-\beta)}$. It is worthwhile noticing that l^* is positive for $\beta < 1/2$; if $\beta > 1/2$, then we have that an increase in l has a negative effect on growth. In other words, as long as applied designs are produced relying more on basic research than on the other input, then the R&D technology alone grants a proper size for spillovers If we imagine a Government able to influence this probability, for instance by suggesting the fields that basic research must investigate, then, depending on the R&D technology characteristics, it should choose to patronize research fields with a probability of economic exploitation as close as possible to the threshold level, l^*, whenever the multi-stage R&D process does not rely intensely on basic research. But it should instead champion research fields with a low probability of economic exploitation, whenever the multi-stage R&D process relies intensely on basic research.

It should be noted that, for l approaching 1, growth goes to zero, whereas in the single-industry economy, growth is increasing. Again, the different outcome is due to cross-industry influences: non arbitrage in asset market channel the inter industry effect of $(1-l)$ on returns from entry in the D industry on the economy rate of returns. Effects of $(1-l)$ on industry R returns are the same as in the single-industry set up.

The findings about l differ from the single-industry set up. The main reason behind these differences is the novel trajectories opened by cross-industry influences. Moreover, these influences are not simply due to inter-industry spillovers, as also prices channel important effects. Eq.(3.31) and eq.(3.32) provide a formal explanation of the trajectories we are

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referring to: returns in the industry that does not generate any spillover are affected both by spillovers targeting the industry, E_D, and by spillover targeting the other industry, E_R. The latter reach the D industry trough their effect on prices. Finally, a part from spillovers, the cross-industry price relationship is able to convey influences that cannot be captured in a single industry set up.

Turning to R&D productivity, we see that development productivity in the multi-stage R&D, $(1-l)$, matters for growth, another result which differs from the single industry set up. As we have argued above, it is the linkage between industries that allows for these influences to happen, by channeling them indirectly through prices and directly through spillovers.

Then, productivity of basic research exerts two effects: positive influence through the reduction of the entry cost, and a negative one through the reduction in the basic research applied design ratio. The global effect of basic research externalities on the rate of returns is positive, as showed in eq.(3.32). Therefore, as an increase in productivity of development in the basic-research-intensive industry reduces the ratio of basic research over applied designs, ceteris paribus, there is a negative impact on spillovers. The same arguments works for an increase in basic research productivity, as the benefits it generates on applied design creation are greater than the direct benefits on basic research creation. Overall, the positive effect prevails.

Finally, productivity if development in the D industry plays a negative effect on growth, even if it reduces entry cost, an effect usually leading to positive influences However, being the set up a multi-industry one, the consequent increased entry in the D industry generates

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an increase in Y_D, that, in turns, makes the price P_D fall down. Then, the reduction in P_D is followed by an increase in P_R, as stressed by eq.(3.6). As producing Y_R is more convenient than before, workers are shifted away from R&D to final good production. This lowers the equilibrium value of $\frac{M_R}{N_R}$ and consequently growth.

Overall, disentaglement of industries according to the kind of R&D performed and to spillovers unravels the mechanisms through which R&D components propagate throughout the whole economy and offers outcomes which cannot be captured if the economy is treated as homogeneous in terms of industry. As empirical evidence assesses the importance of R&D spillovers (inter and intra sector) on productivity growth, this model provides a possible theoretical explanation on the way this influence takes place and its effects

The Scale Effect It is straightforward to notice that eq.(3.36) does not depend on the size of the labour force which is employed in the R sector, $\bar{L}_R$. Therefore, an increase in the labour force does not have any effect on the growth rate. This result is consistent with empirical evidence on the effect of population on growth. However, we need to point out that a scale effect is still at work with respect to sector D -specific input used in the production of the sector-specific final good, $\bar{L}_D$. Anyway, this sector-specific input does not need to be labour: it can be easily thought as land or capital (Acemoglu, 2002).

The scale effect disappears thanks to the two features which have been introduced in the economy to account for the relevant characteristics of basic research-intensive R&D -multi stage research processes and spillovers- and of their effects on the rate of return. As usual,

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free entry condition in industry R implies

$$r = \frac{l\pi_{RMon}}{\hat{p}_R}$$

where π_{RMon} is defined by eq.(3.21) and $\hat{p}_R$, after non arbitrage in labour market has been enforced, by eq.(3.29). After some substitutions, we see that an increase in population exerts two opposite effects on the rate of return. On the one hand, a positive shift in $\bar{L}_R$, by increasing demand for intermediate goods, plays a positive effect on r through an increase in monopolistic profits. This is the standard channel through which the scale effect influences equilibrium in horizontal innovation models. However, in this economy there is another channel through which the scale of the population affects equilibrium: the same positive shift in $\bar{L}_R$ has a positive influence also on the price for a blueprint. In equilibrium, the two effects cancel out.

3.2.4 Decentralized equilibrium and BGP with erosion of monopoly power

We have analyzed the equilibria of an economy in which erosion of monopoly power in the development-intensive sector was ruled out. Now, we face the more general case, in which erosion on monopoly power does take place in industry D.

We assume that the probability of an intermediate good in the D sector transforming from monopolized to competitive is generated from a Poisson process as done in the literature (Barro and Sala-I-Martin, 2004; Gancia and Zilibotti, 2003). The parameter characterizing the Poisson process has been previously labelled p. Now, we assume that p is a function

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of variables characterizing the economy, following well-established works (Segerstrom, 1998; Barro and Sala-I-Martin, 2004).

We assume that basic research helps reducing the probability of erosion of monopoly power, by shifting upward the frontier of knowledge; therefore, p depends negatively on Q. On the contrary, erosion of monopoly power in the development-intensive-industry increases as the size of the economy increases, as this determines an augmented menu of existing varieties, making it more difficult to avoid close substitute goods where there are no breakthrough innovations. We proxy the size of the economy with the size of the intermediate good sector in the most innovative industry, lN_Rx_R. Formally, the Poisson process is governed by

$$p = \frac{lN_Rx_R}{Q}. \tag{3.37}$$

Now that $p \neq 0$, there is another state variable in the economy, given by the stock of D intermediate goods having turned competitive, N_{DC}. If N_D and N_{DC} are big enough, then the law of motion for N_{DC} is given by $\dot{N}_{DC} \simeq p(N_D - N_{DC})$, with p defined by eq.(3.37). Note that erosion of monopoly power in the D sector depends on entry in the R sector.

3.2.4.1 BGP

Proposition 3.2 As long as all research stocks grow at the same rate and $\frac{\dot{N}_{DC}}{N_{DC}} = \frac{\dot{N}_D}{N_D}$, then the Poisson parameter given by eq.(3.37) is constant. Therefore, all variables in the economy grow at the same rate, given by $\frac{\dot{N}_R}{N_R} = \frac{(1-l)^\beta}{\eta_Q^{1-\beta}} L_{NR}^\beta \left(\frac{M_Q}{N_R}\right)^{1-\beta}$.

Proof. Proof of Proposition 2.4 follows from Proof of Proposition 2.1. We just need to

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note that $\frac{\dot{Y}}{Y} = \frac{\dot{N}_D}{N_D}$ only if N_D and N_{DC} grow at the same rate. By adding this assumption to the one stating that all research stocks grow at the same rate, we get that all variables grow at the same rate ■

3.2.4.2 Decentralized Equilibrium

The process driving to the definition of the decentralized equilibrium for this economy is the same that we have followed above when erosion of monopoly power was ruled out. We simply have to substitute the value for p given by eq.(3.37) inside eq.(3.7) and repeat the same steps we have described above. Eq.(3.7) becomes

$$V_D = \frac{\pi_{DMon}}{r + \frac{lN_R x_R}{Q}}. \tag{3.38}$$

Profit maximization problem for Y_D producers becomes

$$\max_{x_{DC}, x_{DMon}} P_D Y_D - w_D \bar{L}_D - \int_0^{N_D - N_{DC}} \tilde{p}_{jDMon} x_{jDMon} dj - \int_0^{N_{DC}} \tilde{p}_{iDC} x_{iDC} di$$

where $Y_D = E_D^{1-\alpha} \left(\int_0^{N_D - N_{DC}} x_{jDMon}^{\alpha} dj + \int_0^{N_{DC}} x_{iDC}^{\alpha} di \right) \bar{L}_D^{1-\alpha}$ and $\tilde{p}_{iDC}$ is the price of the ith competitive intermediate good in sector D. From this profit maximization we get the inverse demand functions for x_{jDMon} and x_{iDC}, where the first is still given by eq.(3.16), and the second by $\tilde{p}_{DC} = P_D E_D^{1-\alpha} \alpha x_{DC}^{\alpha-1} \bar{L}_D^{1-\alpha}$. As a consequence, we have that the expression for π_{jDMon} is still given by eq.(3.20), while $p_{DC} = 1$, $x_{DC} = [\alpha P_D]^{\frac{1}{1-\alpha}} E_D \bar{L}_D$and $\pi_{DC} = 0$. In

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sector R nothing changes. Therefore, the system characterizing the equilibrium is given by

$$r_D = \frac{\left(\frac{1-\alpha}{\alpha}\right)\alpha^{\frac{2}{1-\alpha}}}{\eta_D} P_D^{\frac{1}{1-\alpha}} E_D \bar{L}_D - l\alpha^{\frac{2}{1-\alpha}} \frac{E_R P_R^{\frac{1}{1-\alpha}} N_R \left(\bar{L}_R - L_{NR}\right)}{Q} \tag{3.39}$$

together with eq.(3.6), eq.(3.4),eq.(3.5), eq.(3.30), eq.(3.31) and the Euler equation. Note that basic research spillovers have a positive effect on the probability of erosion: the more knowledge disseminates, the easier it gets have enough abilities to imitate and create close substitutes. The solution for this system is given by

$$\gamma' = \frac{\rho}{\left(1 + \frac{1}{(1-\beta)(1-\alpha)\beta}\right)\Phi - \sigma} \tag{3.40}$$

where $\Phi = \alpha\beta\frac{\eta_Q}{\eta_D}\left[\beta(1-\beta)^{\frac{\beta}{1-\beta}}\right]^{\frac{1}{1-\alpha}}\left[\frac{(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}(1-\beta)^{\beta}l^{2\beta-1}}{\beta^{\beta}(1-l)}\right]^{\frac{1}{1-\beta}}\xi\bar{L}_D$.

Proposition 3.3 The introduction of erosion of monopoly power in the industry which does not perform basic research lowers the equilibrium value for the growth rate.

Proof. Take eq.(3.36) and eq.(3.40), it is straightforward to see that $\gamma > \gamma'$ means

$$\frac{\Phi}{(1-\beta)(1-\alpha)\beta} > 0$$

which always holds. ■

So, erosion of monopoly power harms growth, by reducing returns from entry.

With respect to comparative statics, the same findings we have described without erosion

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of monopoly power apply

3.3 Social Planner and R&D Policy

In the baseline horizontal innovation framework, the decentralized equilibrium is notoriously inefficient, due to monopolistic competition. Our framework contains ingredients that may either strengthen or weaken this finding. In this section we demonstrate that the outcome in the decentralized economy is not Pareto optimal. We know already that the economy presents many causes for market failure: monopolistic competition, erosion of monopoly power, externalities,... In order to assess Pareto optimality, we compare the BGP growth rate of the decentralized economy with the corresponding growth rate determined by the social planner.

The planner maximizes the utility of the representative household taking into consideration the economy-wide resource constraint and the laws of motion for R&D. The solution of this maximization problem implies that planner solution differs from the solution determined by the decentralized economy[8].

3.3.1 Optimal Fiscal Policy to Reach Pareto Optimality

We have shown that the decentralized outcome fails to be Pareto optimal. However, the Government can induce the private sector to attain the social optimum in a decentralized setting by engineering an appropriate tax-subsidy policy. Here we consider a menu of fiscal instruments suitable to reach the first best both when we rule out erosion of monopoly power

[8] The analytical treatment of the Social Planner problem can be found in Appendix B.

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and when we allow for it.

3.3.1.1 No Erosion of Monopoly Power

The economy presents the following distortions: monopolistic competition, positive spillovers from basic research and negative congestion effect from secrecy efforts. At first sight, these are the same distortions characterizing the single- industry economy discussed in Chapter 2. However, a closer look reveals immediately that some of them follow different trajectories in the multi-industry set up: both positive spillovers from basic research and negative congestion from secrecy efforts diffuse both inter and intra sector. Moreover, the inter-industry price relationships constitute another channel through which spillovers move. As a consequence, the optimal fiscal policy will differ from the one designed for the single-industry economy.

The various tools belonging to the optimal fiscal policy are:

(*i*) subsidy to basic research activity on input purchase, θ_q, such that $(1-\theta_q) = \frac{(1-\alpha)(1-l)^{\beta} l(1-\beta)}{1+(1-\beta+\Gamma)\left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)}$, where Γ is a function of parameters[9].The optimal fiscal policy has to promote basic research accumulation, as private agents do not internalize positive spillovers from basic research;

(*ii*) Subsidy to intermediate good purchasing to induce marginal cost pricing in intermediate good market, without eliminating the proper incentive to create new varieties. This subsidy takes the usual form: $(1-\theta_x) = (1-\alpha)$ in both sectors;

[9] Γ is determined in Appendix B.

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(*iii*) the optimal fiscal policy must control for the negative externality effect generated by efforts to enforce secrecy around basic research ideas. This task is pursued by lowering the incentive to start up new intermediate good producing firms. by setting a tax on households' asset income In this way, incentive to enter in both industries decreases. Formally, tax on households' asset income is given by $\tau_H = \frac{(1-\beta^2)\left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)}{\beta[1+(1-\beta)\left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)}$; then, as congestion operates both inter and intra-industry, we also introduce a tax on Y_R purchase. The tax reduces, ceteris paribus, the basic research over applied designs ratio, by reducing the relative size of industry R intermediate good sector, $\frac{N_R}{N_D}$. Congestion is softened. This tax is given by $\tau_{YR} = 1 - \Phi$[10]

(*iv*) besides congestion generated by R industry patent holders, there is a positive externality effect exerted by the stock of useless applied designs created in the same industry on development. So, in industry R there are two opposite externalities spurring from the same activity. This implies another tool, which is specific to industry R, targeting labour employment in final good production, L_{YR}. This tool is formally given by $(1 - \theta_{YR}) = \frac{L_{NR}}{\bar{L}_R - L_{NR}}$. Transversality conditions imply that $\frac{L_{NR}}{\bar{L}_R - L_{NR}} < 1$, meaning that θ_{YR} is a subsidy. Subsidizing employment in Y_R reduces the entry cost in the same industry, but, at the same time, it increases, ceteris paribus, the amount of basic research used to produce an applied design, as can be seen looking at eq.(3.29);

(*v*) R&D cost in industry D (that is the cost for acquiring a blueprint made exclusively of

[10] $\Phi = \frac{1}{(1-\beta)^{1+2\beta+\alpha\beta(1-\beta)}\beta^{1-\alpha\beta^2--2\beta(1-\alpha)}(1-l)^{(1-\beta)(1-\alpha)\beta}}$

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development activity) must be taxed, at a rate given by $(1+\tau_D) = \Sigma^{11}$. In this way, it gets relatively more convenient to enter in the R industry, that is the industry where the positive spillovers affecting also industry D are created.

There are several implications for this optimal fiscal policy. First, basic research is the unique research activity deserving fiscal treatment: it has to be subsidized to account for its positive spillovers. So, it is optimal for the Government to set an R&D policy explicitly directed towards basic research and not towards R&D activity in general. Second, R&D relying on development activity only is indeed taxed.

To conclude, we have found support for the issue that "*whether growth will be enhanced by a subsidy to innovation might depends crucially on whether product or process innovations are subsidized, or on whether basic or applied research is encouraged by the subsidy*" (Aghion and Howitt, 1999).

3.3.1.2 Erosion of Monopoly Power

Erosion of monopoly power in the D sector increases the gap between private and social rates of return. Whenever the relative productivity is below this threshold level, the gap is reduced, but it does not disappear. Therefore, we can infer that the optimal fiscal policy must account for all the distortions listed above, plus the reduced willingness to start up new firms in industry D due to erosion of monopoly power. In fact, in this case optimal fiscal policy keeps the menu of fiscal instruments listed in the previous paragraph and adds a

[11] $\Sigma = \frac{\bar{L}_D^{\beta}\eta_Q^{\beta(1+\beta)}}{l^{\beta+1}(1-\alpha)^{\frac{1-\alpha\beta-\beta}{(1-\alpha)(1-\beta)}}}$

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new tools specifically aimed at compensating for erosion of monopoly power in the D sector. This instrument take the form of a lump sum transfer to intermediate good producers in industry D given by $p\eta_D$.

The last subsidy is needed to stimulate entry in the D sector when there is erosion of monopoly power.

3.4 Technological Imitation.

Some empirical works have highlighted that, even though technological innovation is crucial to economic growth, only a small group of industrial countries account for most of the world's innovation (Helpman and Hoffmaister, 1997). Within the OECD, the seven largest economies accounted for over 90% of R&D in 1991; more in general, in 1990, industrial countries accounted for 96% of the world's R&D expenditure (Helpman and Hoffmaister, 1997). This evidence suggests that there is a huge difference among countries with respect to innovation. Moreover, also basic research investments are concentrated within developed countries: "*from an empirical standpoint, we may be able to identify technological leaders with a group of advanced countries, such as the United States, Japan, Germany, and so on. Each of these country caries out leading-edge research in certain areas. Technological follower corresponds to the array of follower, less developed countries, which carry on no significant basic research*"(Barro and Sala-I-Martin, 1997). These facts suggest that the growth model analyzed before could be suitable to address also the study of the international context.

We adapt the set up to model a situation where few countries innovate and the rest

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of the world innovate along the margin and imitate. To capture the difference, we assume that innovating countries invest in basic research, whereas imitating countries perform R&D investments with poor innovation content and benefit from imitation of innovating countries. We also account for the fact that basic research spills also internationally (Funk, 2002).

3.4.1 Set up

The leader-follower model presented below is a variant of the two-industry set up analyzed above. We group world countries in two main sets: innovators and imitators. The former set is made of developed countries: they invest in basic research. The latter is made of developing countries: they just innovate along the margin of their knowledge and imitate existing knowledge. The model economy consists of three sectors: final-good sector which is perfectly competitive and produces consumption goods. The monopolistically competitive intermediate-goods sector that supplies a variety of inputs to the final-good's producers. Finally, the R&D sector that supplies the intermediate-goods producer with different designs/blueprints.

Consider two countries: the technological follower is country D whereas the technological leader is country R. The production functions are respectively given by eq.(3.3) and eq.(3.2), which we rewrite here for simplicity

$$
\begin{aligned}
Y_D &= E_D^{1-\alpha}\left(\int_0^{N_D} x_{jDMon}^{\alpha} dj\right)\bar{L}_D^{1-\alpha}, \\
Y_R &= E_R^{1-\alpha}\left(\int_0^{lN_R} x_{jRMon}^{\alpha} dj\right)L_{YR}^{1-\alpha}
\end{aligned}
$$

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Here we assume that Y_R is physically identical to Y_D.Final goods are tradable across countries. They are exchanged at a single world price that we normalize to unity. Moreover, we assume that trade is balanced between the two countries: domestic output equals aggregate domestic expenditures. E_D and E_R are given by eq.(3.4) and eq.(3.5).

Intermediate goods do not move freely between countries as their adoption in final good production requires expertise supervision. In country R, where there is no imitation, the producer of any intermediate good provides this supervision, whereas, for imitated goods a local expert must be enrolled. Obviously, the local expert has to be paid. Therefore copying is a costly activity. We assume that imitators pays no fee to inventors, so that imitation implies the adaptation cost only.

Besides imitation, there is invention, which is a costly activity creating new varieties. In industry D both activities are possible. In industry R people just innovate.

Consider the leading country first. Dealing with country R alone equals to the set up analyzed in Chapter 2. The equations characterizing the decentralized equilibrium for this economy are

$$\begin{aligned}
L_{NR}^{\beta} &= \frac{(1-\beta)(1-\alpha)l\alpha^{\frac{2\alpha}{1-\alpha}}}{\eta^{1-\beta}(1-l)^{\beta}\beta}\left(\frac{M_Q}{N_R}\right)^{\beta-1}, \\
r_{entryR} &= \frac{\alpha\beta(1-l)^{\beta}\left(\frac{M_Q}{N_R}\right)^{1-\beta}\left(\bar{L}_R - L_{NR}\right)L_{NR}^{\beta-1}}{\eta^{1-\beta}} \\
r_{savingsR} &= \frac{\sigma(1-l)^{\beta}}{\eta^{1-\beta}}L_{NR}^{\beta}\left(\frac{M_Q}{N_R}\right)^{1-\beta} + \rho = \sigma\gamma_R + \rho
\end{aligned} \tag{3.41}$$

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which, using non arbitrage in asset market, give

$$\left(\frac{M_Q}{N_R}\right)^{1-\beta} = \frac{\rho\eta^{1-\beta}}{(1-l)^{\beta}\left[\alpha\beta\left(\frac{\bar{L}-L_N}{L_N}\right)-\sigma\right]L_{NR}^{\beta}}. \tag{3.42}$$

from which we get

$$\gamma_R = \frac{(1-\alpha)(1-\beta)l\alpha^{\frac{2\alpha}{1-\alpha}}}{\beta}. \tag{3.43}$$

Turning to the follower country, D, we model this country following the features of the D industry analyzed above. To account for costly imitation, we assume that the numbers of goods that can be copies is limited to the finite number that has been discovered elsewhere. The cost for adapting an uncopied R variety is endogenous: following the literature, we assume that it depends positively on the ratio of copied goods over the pool of total varieties discovered elsewhere, N_D/N_R, as the goods which are easier to imitate are copied first (Barro and Sala-I-Martin, 1997). Formally, we define the cost for imitation $\phi_D = \phi_D\left(\underset{+}{N_D}, \underset{-}{N_R}\right)$, $\phi_D' > 0$, $\phi_D'' \geq 0$. We also rule out both complete imitation and absence of imitation.

Once a good has been imitated, the imitator retains perpetual monopolistic profits from its employment in Y_D production.

To determine the equilibrium growth rate in country D, we go through the usual steps. We have just to remember that in this country there is also an imitation cost.

As long as imitating is cheaper than innovating, in country D no discovery is made. Formally, this happens whenever $\eta_D > \phi_D$. Entrants simply add varieties of intermediate

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goods by adapting varieties discovered in the other country. Whenever this is the case, the returns from entry along the BGP are given by

$$\begin{aligned} r_{entryD} &= \frac{(1-\alpha)\,\alpha^{\frac{2}{1-\alpha}} E_D \bar{L}_D}{\alpha \phi_D} + \frac{\dot{\phi}_D}{\phi_D} \\ r_{savingsD} &= \sigma \gamma_D + \rho. \end{aligned} \tag{3.44}$$

Clearly, we are assuming that the preference parameters, σ andρ, are the same in both countries.

3.4.2 BGP and Technological Leadership Switchowers.

We consider the case in which imitating is cheaper than innovating in country D. This assumption implies that country D does not have any incentive to innovate and that country R will never imitate as there are no pool from which country R can copy.

If we assume that the world economy is along the Balanced Growth Path, then, M_Q, N_R and N_D grow at the same rate, given by eq.(3.43). Then, ϕ_D is constant and eq.(3.44) simplifies to

$$r_{entryD} = \frac{(1-\alpha)\,\alpha^{\frac{2}{1-\alpha}} E_D \bar{L}_D}{\alpha \phi_D}. \tag{3.45}$$

As the growth rate of country D equals the growth rate of country R and the preference parameters, σ and ρ, are the same in both countries, we have that

$$r_{entryD} = r_{entryR} = \frac{l \pi_R}{\hat{p}_R}. \tag{3.46}$$

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And this result holds because the growth rate must be equal. We do not need to assume a common asset market.

We use the equality stressed in eq.(3.46) to solve for the imitation cost. We substitute for r_{entryD} using eq.(3.45) and for r_{entryR} using eq.(3.41). We also substitute for E_D using eq.(3.5). Then, we specify that $\phi_D = \frac{N_D}{N_R}$. Using this specification we find

$$r_{entryD} = \frac{(1-\alpha)\,\alpha^{\frac{2}{1-\alpha}}\bar{L}_D}{\alpha} E_D \left(\frac{N_R}{N_D}\right) \tag{3.47}$$

which we set equal to r_{entryR} to find

$$\frac{N_D}{N_R} = \hat{p}_R \left(\frac{E_D}{E_R}\right)\left(\frac{\bar{L}_D}{L_{YR}}\right) \tag{3.48}$$

showing that the gap between leader and follower in terms of varieties depends positively on relative strength of basic research spillovers and on country size. The stronger the relative influence of basic research on the follower, the more the inter country gap gets reduced. In the baseline model of technological diffusion, the gap depends on country size and on country-specific productivity parameters. Here, the country size effect is still at work, but idiosyncratic productivity is replaced by and endogenous variable that is driven by country R.

As we are dealing with a world economy where the follower has no incentive to innovate as the cost of innovation is above the cost of imitation, eq.(3.48) is useful to determine the

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following relationship

$$\eta_D > \hat{p}_R \left(\frac{E_D}{E_R} \right) \left(\frac{\bar{L}_D}{L_{YR}} \right).$$

Let us imagine that some exogenous circumstances intervene to reverse the relationship between innovating and copying in country D. Formally, this means that along the BGP $\eta_D < \phi_D$. Whenever this is the case, country D creates new varieties and country R could consider to imitate them. Counry D innovates according to a simple R&D process where only development is carried on. This is not only a consequence of being a follower, but it is also consistent with reality: developing countries do not shift from imitation to basic research-intensive R&D.

In baseline models of technological diffusion and innovation, whenever the cost of innovation falls below the cost of imitation for the technological follower, technological leadership switches from the technological leader to the follower in equilibrium. In this set up, the influence exerted by basic research towards final good productivities. in both countries breaks down this result. To see how, consider that, for imitation to take place in country R, $\phi_R < \hat{p}_R$ must hold. Then, symmetrically to country D, $\phi_R = N_R/N_D$. Using eq.(3.46), we get $\phi_R = \pi_R \eta_D / \pi_D$, which we use to write

$$\frac{\pi_R \eta_D}{\pi_D} < \hat{p}_R.$$

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Which we simplify by substituting for π_R and π_D:

$$\frac{E_R L_{YR} \eta_D}{E_D \bar{L}_D} < \hat{p}_R.$$

Substituting for E_R and E_D using eq.(3.4) and eq.(3.5) and recalling eq.(3.27), it is straightforward to see that the inequality does not hold, as the left hand side will increase as soon as basic research stops accumulating. Therefore, the leading country will never stop innovating and technological leadership never switches.

Therefore, the introduction of multistage R&D processes and the consequent possibility of modelling spillovers effect from each R&D components rule out the possibility that technological leading countries gets overcome by followers. The underlying motivation relies on basic research: leaders are such because they invest in fundamental research, thus getting breakthrough innovations and the consequent benefits acknowledged by the literature. The positive effects generated by basic research both at domestic and international level are such that returns in both countries get too much harmed if basic research stops being created.

This result supports empirical evidence showing that top countries in the technological leadership ranking persist for extremely long time horizon and that most countries have never been technological leaders (Barro and Sala-I-Martin, 1997)

3.5 Conclusion

Economic literature highlights sound differences between basic research and development. Broad evidence shows that both activities are performed, also by firms, and that industries

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can be grouped in two wide subsets depending on the R&D process they perform: relatively more basic-research-intensive and relatively more development-intensive. Moreover, there is evidence of significant inter-industry spillovers from basic research.

The consequences on growth of distinguishing between R&D activities has been analyzed in Chapter 2, producing meaningful results. In this chapter, we have extended the framework to account also for differences among industries and inter-industry R&D spillovers.

The model presented in this chapter presents a closer fit to the facts about private R&D as it accounts also for observed differences among industries. Moreover, it delivers results that cannot be embedded in the single-industry set up: some of the findings are indeed different from the one determined in the single-industry economy. The main source for distinction are the wider menu of R&D spillovers and the interdependencies between industries.

In the single-industry economy of Chapter 2, the effect of R&D spillovers on returns from investment is just indirect, whereas in the multi-industry framework R&D spillovers impact both directly and indirectly on returns. Moreover, the overall impact is different.

Therefore, it is not simply a different knowledge dissemination mechanism leading to similar outcomes: wider trajectories for R&D externalities generate novel consequences on the economy.

We have also introduced erosion of monopoly power in the development-intensive industry, since it seems plausible that the low level of innovation pairs with proliferation of close-substitute patents.

The main differences in terms of results refer to the effects of the characteristics of R&D

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processes and to optimal fiscal policy.

First, the size of labour force does not play any scale effect, as well as the size of scientists.

Second, the possibility of economic useless investments in basic research plays two opposite effects on growth. There is a positive effects from spillovers exerted on R&D productivity in their own sector and a negative effect on private incentive to invest in research from the possibility that a basic research investment may proof to be economically useless. Overall, we find that, as long as the probability of economic exploitation is low, an increase in the probability benefits growth, as the increase in the incentive to entry prevails, whereas for higher starting values for the probability, the same increase damages growth as the higher R&D cost offsets the positive increase in expected profits.

Third, research activities have different effects on growth. An increase in development productivity in D industry harms growth, by shifting away resources from the R&D activities generating spillovers. Productivity of basic research productivity plays two opposite influences on the growth rate: on the one hand, by reducing the entry cost that firms must bear, it increases willingness to enter, whereas on the other hand, the same reduction in entry cost makes the number of innovators in the basic research intensive sector increase, thus reducing resource availability to produce basic research per innovator. The whole influence is positive.

Others interesting findings arise in terms of welfare as basic research spillovers, together with other features of the economy, imply that the decentralized outcome fails to be Pareto optimal. With respect to fiscal policy, the Government can implement an optimal fiscal policy

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which subsidizes the basic-research-intensive R&D, but levies taxes on the development-intensive industry R&D. The differences in fiscal treatment of the various research activities are due to the key role of externalities from research on productivity.

To conclude, literature on horizontal innovation has established that R&D is a key element to sustain growth and that, usually, R&D implies adoption of fiscal policy to offset market failures. As a consequence, many contributions have been developed to study the possibilities for improving on decentralized outcomes by means of fiscal policies, but R&D has always been treated as an homogeneous good. The policy agenda of many developed countries have been influenced by these policy advice, setting fiscal support for R&D with no distinction between privately performed basic research and development. The policy advice from this model is different, since it hinges on the finding that basic research should be always helped, whereas support for development should be neglected.

3.6 Appendix A: Economy-wide Resource Constraint

Households' budget constraint is given by

$$C + \dot{a} = w_Y L_Y + w_N L_N + ra$$

where a denotes households'asset. In this economy, we assume that assets consist of the shares of intermediate good firms and shares of R&D firms. Since the economy is closed, households own the total number of shares. Returns from being firms owners are given by the sum of dividends paid out each period and capital gain (or losses), where dividends are given

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by the net cash flow. The value of a claim on intermediate good producing firms at time t in industry h, $h = D, R$, is given by V_h. Thus, the aggregate value of claims on intermediate good firms owned by households is equal to $lV_R N_R + V_D N_D$. Then, the aggregate R&D firms give only dividends, $d_h \dot{N}_h$, $h = D, R$. As usual, non arbitrage in capital market implies that households will be willing to hold the claims on firms only if their total returns match the returns to a perfectly substitutable and safe asset of size $a \equiv (V_N l N + +V_D N_D)$ (Acemoglu, 2002), and aggregate dividends from R&D firms are given by their aggregate net cash flow. Therefore

$$r\left(V_N l N + +V_D N_D\right) + d_R \dot{N}_R + d_D \dot{N}_D = l\tilde{\pi}_R N_R + l\tilde{\pi}_D N_D + \quad (3.49)$$
$$+\frac{\hat{p}_R (1-l)^\beta}{\eta_Q^{1-\beta}} M_Q^{1-\beta} N_R^\beta L_{NR} - w_{NR} L_{NR} - M_Q + \frac{\hat{p}_D}{\eta_D} M_D - M_D$$

Since we are carrying out a balanced growth path analysis, capital gains (losses) are zero, $\dot{V}_h = 0$, $h = D, R,$. Therefore, using eq.(3.49), the households' budget constraint changes as follows

$$C + V_R \dot{N}_R + V_D \dot{N}_D = w_{YD} L_{YD} + w_{YR} L_{YR} +$$
$$+\tilde{\pi}_D N_D + l\tilde{\pi}_R N_R + \frac{\hat{p}_R (1-l)^\beta}{\eta_Q^{1-\beta}} M_Q^{1-\beta} N_R^\beta L_{NR}^\beta - M_Q + \frac{\hat{p}_D}{\eta_D} M_D - M_D$$

Recall that final good sector is competitive, therefore, $w_{Yh} = (1-\alpha) Y_h$, $h = D, R$. Free entry in intermediate good production gives $V_h = \hat{p}_h, h = D, R$. Moreover, recalling that $\dot{N}_R = \frac{(1-l)^\beta}{\eta_Q^{1-\beta}} M_Q^{1-\beta} N_R^\beta L_{NR}^\beta$ and using the equilibrium expressions for $\tilde{\pi}_h$ and Y_h, $h = D, R$, we

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get the economy-wide resource constraint

$$C + M_D + M_R + lN_R x_{RMon} + N_D x_{DMon} = Y$$

3.7 Appendix B: The Social Planner Problem

The planner maximizes the utility of the representative household taking into consideration the economy-wide resource constraint and the law of motion for the state variables:

$$\max_{C, x_{hMon}, x_{DC}, M_h} \int_0^\infty e^{-\rho t} \left(\frac{C^{1-\sigma} - 1}{1-\sigma} \right) dt, \;\; h = D, R$$

$$s.t. \qquad \begin{aligned} \dot{N}_D &= \frac{1}{\eta_D} M_D \\ \dot{N}_R &= \frac{(1-l)^\beta}{\eta_Q^{1-\beta}} M_Q^{1-\beta} N_R^\beta L_{NR}^\beta \\ q &= \frac{1}{\eta_Q} \frac{M_Q}{\dot{N}_R} \\ C + lN_R x_{RMon} + (N_D - N_{DC}) x_{DMon} + N_{DC} x_{DC} + M_Q + M_D &= Y \\ Y_R^{1-\beta} Y_D^\beta &= Y \\ & N_{R0}, N_{D0} \end{aligned}$$

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Remembering that $Q = N_R q$, we write the current value Hamiltonian for this problem as

$$\begin{aligned} H &= \frac{C^{1-\sigma}-1}{1-\sigma} + \nu \frac{1}{\eta_D} M_D + \mu \frac{(1-l)^\beta}{\eta_Q^{1-\beta}} M_Q^{1-\beta} N_R^\beta L_{NR}^\beta + \\ &+ \lambda \left[Y_R^\beta Y_D^{1-\beta} - C - l N_R x_{RMon} - (N_D - N_{DC}) x_{DMon} - N_{DC} x_{DC} - M_R - M_D \right] \end{aligned}$$

The relevant FOCs for this problem are

$$C^{-\sigma} = \lambda \tag{3.50}$$

$$\frac{\alpha\beta l^{\beta-1}\Psi^{1-\alpha}\bar{L}_D^{(1-\alpha)(1-\beta)}}{L_{NR}^{(1-\alpha)\beta^2}} \left(\frac{N_D}{N_R}\right)^{1-\beta} \left(\frac{M_Q}{N_R}\right)^{(1-\alpha)\epsilon} \left(\frac{x_D}{x_R}\right)^{\alpha(1-\beta)} \left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)^{(1-\alpha)\beta} = x_R^{1-\alpha} \tag{3.51}$$

$$\frac{\alpha(1-\beta)\Psi^{1-\alpha}l^\beta\bar{L}_D^{(1-\alpha)(1-\beta)}}{L_{NR}^{(1-\alpha)\beta^2}} \left(\frac{N_D}{N_R}\right)^{-\beta} \left(\frac{M_Q}{N_R}\right)^{(1-\alpha)\epsilon} \left(\frac{x_R}{x_D}\right)^{\alpha\beta} \left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)^{(1-\alpha)\beta} = x_{Dh}^{1-\alpha}, h = C, Mon \tag{3.52}$$

$$\begin{aligned} &\lambda \left[1 - \frac{\beta\Psi^{1-\alpha}(1-\alpha)\epsilon l^\beta \bar{L}_D^{(1-\alpha)(1-\beta)}}{L_{RN}^{\beta^2(1-\alpha)}} \left(\frac{M_Q}{N_R}\right)^{(1-\alpha)\epsilon-1} \left(\frac{N_D}{N_R}\right)^{1-\beta} \left(\frac{x_R}{x_D}\right)^{\alpha\beta} \left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)^{(1-\alpha)\beta} x_D^\alpha \right] \\ = \; &\mu \frac{(1-l)^\beta(1-\beta)}{\eta_Q^{1-\beta}} \left(\frac{M_Q}{N_R}\right)^{-\beta} L_{RN}^\beta \end{aligned} \tag{3.53}$$

$$\lambda = \frac{\nu}{\eta_D} \tag{3.54}$$

$$\begin{aligned} &\lambda \frac{x_D^\alpha}{L_{RN}^{\beta^2(1-\alpha)}} \left(\frac{M_Q}{N_R}\right)^{(1-\alpha)\epsilon} \left(\frac{N_D}{N_R}\right)^{1-\beta} \left(\frac{x_R}{x_D}\right)^{\alpha\beta} \left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)^{(1-\alpha)\beta} \left(\frac{1}{\bar{L}_R - L_{NR}} + \frac{1-\beta}{L_{NR}}\right) \\ = \; &\mu \frac{(1-l)^{\beta+\beta^2(1-\alpha)}\beta}{\eta_Q^{1-\beta}(1-\alpha)\beta l^\beta \Psi^{1-\alpha}\bar{L}_D^{(1-\alpha)(1-\beta)}} \left(\frac{M_Q}{N_R}\right)^{1-\beta} L_{RN}^{\beta-1} \end{aligned} \tag{3.55}$$

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$$\frac{\lambda}{\mu}\left\{\frac{[\beta-\epsilon(1-\alpha)]\,\Psi^{1-\alpha}l^{\beta}\bar{L}_D^{(1-\alpha)(1-\beta)}}{L_{RN}^{\beta^2(1-\alpha)}x_D^{1-\alpha}}\left(\frac{M_Q}{N_R}\right)^{(1-\alpha)\beta}\left(\frac{N_D}{N_R}\right)^{1-\beta}\left(\frac{x_R}{x_D}\right)^{\alpha\beta}\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{(1-\alpha)\beta}-l\frac{x_R}{x_D}\right\}x_D$$
$$+\frac{(1-l)^{\beta}\beta}{\eta_Q^{1-\beta}}\left(\frac{M_Q}{N_R}\right)^{1-\beta}L_{RN}^{\beta}=-\frac{\dot{\mu}}{\mu}+\rho \tag{3.56}$$

$$\frac{1}{\eta_D}\left[\frac{(1-\beta)\Psi^{1-\alpha}l^{\beta}\bar{L}_D^{(1-\alpha)(1-\beta)}}{L_{RN}^{\beta^2(1-\alpha)}x_D^{1-\alpha}}\left(\frac{M_Q}{N_R}\right)^{(1-\alpha)\beta}\left(\frac{x_R}{x_D}\right)^{\alpha\beta}\left(\frac{N_R}{N_D}\right)^{\beta}\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{(1-\alpha)\beta}-1\right]x_D=-\frac{\dot{\nu}}{\nu}+\rho \tag{3.57}$$

where $\epsilon=1-\beta+\beta^2$, $\Psi=\frac{\xi^{(1-\beta)}\eta_Q^{(1-\beta)\beta}}{(1-l)^{\beta^2}}$. Note that eq.(3.52) implies that, for the planner, the intermediate goods in the D sector have all the same size. Since $x_{Mon}=x_C$, then N_{DC} disappears from the economy wide resource constraint. Eq.(3.50) together with eq.(3.54) and eq.(3.55) imply that $\gamma_{SP}=\frac{\dot{C}}{C}=-\frac{1}{\sigma}\frac{\dot{\nu}}{\nu}=-\frac{1}{\sigma}\frac{\dot{\lambda}}{\lambda}=-\frac{1}{\sigma}\frac{\dot{\mu}}{\mu}$. Setting eq.(3.51) equal to eq.(3.52) we get

$$\frac{x_D}{x_R}=\left(\frac{1-\beta}{\beta}\right)\frac{lN_R}{N_D} \tag{3.58}$$

We use this result inside eq.(3.51), (3.52), (3.55), (3.56) and eq.(3.57) to get, after some substitutions:

$$x_R=\frac{\Psi\left[\alpha\beta^{1-\alpha(1-\beta)}(1-\beta)^{\alpha(1-\beta)}\bar{L}_D^{1-\beta}\right]^{\frac{1}{1-\alpha}}}{l^{1-\beta}}\left(\frac{N_D}{lN_R}\right)^{1-\beta}\left(\frac{M_Q}{N_R}\right)^{\epsilon}\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{\beta}L_{NR}^{-\beta^2} \tag{3.59}$$

$$x_D=\Psi\left[\alpha\,(1-\beta)^{1-\alpha\beta}\,\bar{L}_D^{1-\beta}\right]^{\frac{1}{1-\alpha}}\left(\frac{lN_R}{N_D}\right)^{\beta}\left(\frac{M_Q}{N_R}\right)^{\epsilon}\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{\beta}L_{NR}^{-\beta^2} \tag{3.60}$$

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$$\frac{\lambda}{\mu}=\frac{\frac{(1-l)^{\beta}(1-\beta)}{\eta_Q^{1-\beta}}\left(\frac{M_Q}{N_R}\right)^{-\beta}L_{RN}^{\beta}}{\left[1-\frac{\epsilon(1-\alpha)\alpha^{\frac{\alpha}{1-\alpha}}(1-\beta)^{\frac{\alpha(1-\beta)}{1-\alpha}}l^{\beta}\bar{L}_D^{1-\beta}\Psi}{\beta^{\frac{\alpha\beta}{1-\alpha}}}\left(\frac{N_D}{N_R}\right)^{1-\beta}\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{\beta}\left(\frac{M_Q}{N_R}\right)^{\epsilon-1}L_{NR}^{-\beta^2}\right]} \tag{3.61}$$

$$\frac{\lambda}{\mu}=\frac{(1-l)^{\beta(1+\beta)}\beta^{\frac{\alpha(1-\beta)}{1-\alpha}}L_{NR}^{\beta^2+\beta}\left(\frac{N_D}{N_R}\right)^{\beta-1}}{\eta_Q^{1-\beta^2}\xi^{1-\beta}l^{\beta}(1-\alpha)\beta^{\frac{1}{1-\alpha}}\alpha^{\frac{\alpha}{1-\alpha}}\bar{L}_D^{1-\beta}(1-\beta)^{\frac{\alpha(1-\beta)}{1-\alpha}}\left(1-\beta+\frac{L_{NR}}{\bar{L}_R-L_{NR}}\right)}\left(\frac{M_Q}{N_R}\right)^{-\beta^2}\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{-\beta} \tag{3.62}$$

$$\frac{\lambda}{\mu}\left\{\frac{l^{\beta-1}\left[\beta-\epsilon(1-\alpha)\right]-\beta\alpha}{\alpha(1-\beta)}\right\}\frac{N_D}{lN_R}x_D+\frac{(1-l)^{\beta}\beta}{\eta_Q^{1-\beta}}\left(\frac{M_Q}{N_R}\right)^{1-\beta}L_{RN}^{\beta}=-\frac{\dot{\mu}}{\mu}+\rho \tag{3.63}$$

$$\frac{(1-\alpha)}{\alpha\eta_D}x_D=-\frac{\dot{\nu}}{\nu}+\rho \tag{3.64}$$

First, we set eq.(3.61) equal to eq.(3.62) to find

$$\frac{N_R}{N_D}=\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{\frac{\beta}{1-\beta}}\left(\frac{M_Q}{N_R}\right)^{-\beta}L_{RN}^{1+\beta}\left[1-\beta+\Gamma+\left(\frac{L_{NR}}{\bar{L}_R-L_{NR}}\right)\right]$$

where $\Gamma=\epsilon\,(1-\alpha)\,\alpha^{\frac{\alpha}{1-\alpha}}\beta^{1+\frac{\beta}{1-\alpha}}(1-\beta)^{\frac{\alpha(1-\beta)}{1-\alpha}}l^{\beta}\bar{L}_D^{1-\beta}\Psi$. Then, we use this expression for $\frac{N_D}{N_R}$ together with eq.(3.60) inside eq.(3.64). Then

$$\Theta\left[1-\beta+\Gamma+\left(\frac{L_{NR}}{\bar{L}_R-L_{NR}}\right)\right]^{\frac{\beta}{1-\beta}}\left(\frac{M_Q}{N_R}\right)^{1-\beta}\left(\frac{\bar{L}_R-L_{NR}}{L_{NR}}\right)^{\frac{\beta}{1-\beta}}L_{RN}^{\beta} \tag{3.65}$$
$$=\quad -\frac{\dot{\nu}}{\nu}+\rho.$$

where $\Theta=\frac{(1-\alpha)\left[\alpha(1-\beta)^{1-\alpha\beta}\beta^{\alpha\beta}\right]^{\frac{1}{1-\alpha}}l^{\beta}\bar{L}_D^{1-\beta}\Psi}{\alpha\eta_D}$. Then, eq.(3.63) together with eq.(3.58), (3.60) and eq.(3.62) implies

$$\begin{aligned} & \frac{(1-l)^{\beta}}{\eta_Q^{1-\beta}} \left\{ \beta - \frac{(1-\beta)^2}{\beta} \left[\frac{\frac{\bar{L}_R - L_{NR}}{L_{NR}}}{1 + (1-\beta)\left(\frac{\bar{L}_R - L_{NR}}{L_{NR}}\right)} \right] \right\} \left(\frac{M_Q}{N_R} \right)^{1-\beta} L_{RN}^{\beta} \\ = \quad & -\frac{\dot{\mu}}{\mu} + \rho. \end{aligned} \tag{3.66}$$

Eq.(3.65) and eq.(3.66) are compared to eq.(3.33) and eq.(3.30) respectively to determine the optimal fiscal policy tools.

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CHAPTER 4

CLEANING THE WORLD DOING MATHS

4.1 Introduction

> "*Tremendous opportunities are offered by research in order to optimize the life cycle of materials and products, and to break the link between environmental impact and economic growth. This is one of the major objectives of European research, which should be pursued for many years to come*". -Philippe Busquin, EU Research Commissioner-

In recent years there has been an increasing interest in extending endogenous growth models to incorporate environmental considerations. In particular, many attempts have focused on the idea that natural environment is indirectly a factor of production as higher quality of environment affects positively productivity of different factors of production (Smulders and Gradus, 1996). Allowing for environmental issues inside the economy leads to concerns about pollution, which is, to date, widely acknowledged to be an inevitable by-product of economic activity and to be directly and negatively related to the level of environmental quality (Bovenberg and Smulders, 1996).

Many contributions have explored the short and long run implications of including pollution in an endogenous growth setting, and an increasing part of them has adopted frameworks

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where innovation plays a key role in abating pollution (Bovenberg and Smulders, 1996; Smulders and Gradus, 1996). However, when environmental issues are embedded in R&D-based growth models or, more in general, when pollution is considered along with innovation, the focus is limited to R&D explicitly pursued to abate pollution. This perspective follows from the fact that privately-performed R&D is production-oriented, and pollution is a negative externality of production; therefore, it is assumed that being R&D carried on by firms for profits motivations, it aims at new product discoveries or cost reduction and, as long as environmental care does not generate profits, firms must be pushed towards pollution-abating R&D investment through Government deeds.

This vision, although widely popular, needs not to encompass all the pathways through which R&D, production and pollution are inter-related. In fact, even if it is undoubtedly true that firms do R&D to increase their profits, it may be the case that some of their R&D exerts some positive effects on pollution-abatement as an unintended by-product. This is indeed the case every time that an improvement in the frontier of knowledge following from R&D activity may also go through new ideas generated in production-oriented activities, opening new and unexpected patterns and processes with positive effects on environmental care.

We claim that this mechanism takes place through the pervasiveness and the novelty of some R&D -namely basic research- and it is channelled through spillovers.

To support our claim we consider well-established economic works on R&D suggesting that the positive side-effects played by R&D spillovers change depending on the R&D ac-

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tivity considered. In particular, basic research is the activity whose spillovers are the most significant and pervasive, whereas development spillovers are the weakest (*i.a.* Auerswald and Branscomb, 2003; Lichtemberg and Siegel 1991; Salter and Martin, 2001). Differences in spillovers strength and diffusion are mainly due to the degree of generality associated to R&D activities: basic research is the most general, therefore the outcomes of an investment in this activity are quite unpredictable and the same holds for the potential directions of its contributions to the stock of knowledge. Given all this, basic research is quite likely to be the best candidate to exert positive consequences on pollution abatement. It is noteworthy that the US Environmental Protection Agency is currently monitoring R&D in nanofields (also privately performed), although not environmental-oriented, to understand and evaluate the positive environmental side-effects (EPA[1], 2005). And nanofield R&D relies heavily on R&D.

Then, recalling the data we presented in the introductory chapter, we see that private agents perform multi-stage R&D processes, where both development and basic research are carried on (NSF[2], 2003). So, there is actual evidence about private R&D processes whose components may modify pollution formation.

The last element we provide to further strengthen our claim about the positive effects of basic research on pollution abatement, even without being directly aimed at environmental targets, is a brief report of some anecdotal evidence about unintended pollution-reducing trajectories of privately performed basic-research-intensive activities. In US and other coun-

[1] Environmental Protection Agency of the United States
[2] National Science Foundation

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tries, such as UK and Japan, nanotech companies are performing R&D processes where basic research has a key role (Ernest and Shetty, 2005; NCMS[3], 2006). Then, several works about nanotechnology roadmapping have highlighted important environmental side-effects of nanotech knowledge: from improved healthcare[4] to environmental care and energy savings (EPA, 2005; Ernets and Shetty, 2005). Other important sectors where R&D has generates fundamental trajectories towards environmental protection, though accidentally, are manufacturing and chemical industry. The former has devoted significant R&D efforts in the plasma physics realm and the outcomes have been manifold: from plasma TV screen to lighter materials and technologies that improve the manufacturing process, mainly with respect to energy cost reduction (ECCR[5], 2002). The latter's R&D efforts towards materials has produced a bulk of knowledge and discoveries about some properties of some materials that allow, for instance, to replace steel with aluminium in vehicles production with a consequent reduction in car weight and fuel usage (AA/USDoE[6], 1999). It has been estimated that the environmental trajectories of nanotech, chemical and manufacturing R&D lead to a potential energy savings for US close to 14.5% of total US energy consumption per year (EPA, 2005). The main environmental-friendly technological trajectories referring to our anecdotal evidence are summarized in Figure 4.1.

[3]National Center for Manufacturing Sciences

[4]It is widely acknowledged that pollution has a positive and significant effect on cancer proliferation and on reducing the quality of life (Arden et al. 2002)

[5]European Comission Community Research

[6]The Aluminium Association, US Department of Energy

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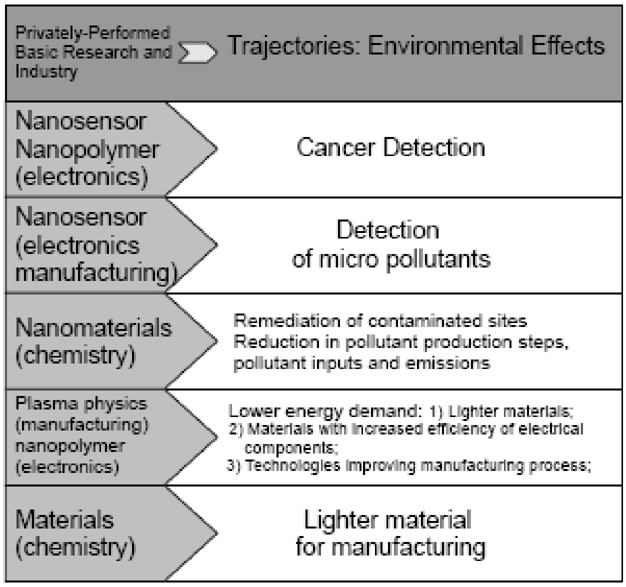

Figure 4.1. Environmental Trajectories of Basic-Research-Intensive Privately Performed R&D.

All these considerations seem to provide enough support to our claim; therefore we develop a framework accounting for the possible unintended effects of privately-performed R&D on pollution, driven by basic research spillovers, to check the consequences in terms of growth and policy-making.

Our perspective may give some appealing insights also with respect to the linkage between R&D and environmental policy. In environmental literature, R&D policy is generally needed to push private firms to perform the socially optimal amount of pollution-abating R&D. However, evidence on federal support to R&D in US shows that different fiscal incentives are used depending on R&D composition and that federal support is mainly directed towards basic research activity. Therefore, by constructing a set up where basic research is

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disentangled from development and contributes accidentally to environmental preservation, it is possible to check whether the observed differences in fiscal incentives play some effects also on environmental care.

The consequences of this exercise may be particularly interesting considering that, notwithstanding well established results on the damages created by pollution, environmental policy gets enforced quite slowly, since efforts towards environmental improvements may be overshadowed by the fear that environmental policy damages the economy through a reduction in production and in economic growth. In fact, there is an active debate between those who argue that, being pollution an inevitable side-product of production, economic growth cannot be ecologically sustainable and those who replicate that a growing economy can produce a growing amount of abatement devices so that pollution is offset (Smulders and Gradus, 1996). Empirical evidence for developed countries seems to support the latter point of view, as there exists substantial evidence that developed countries experience economic growth associated to improvement in environmental quality and that this is achieved through policy enforcement (Grossman and Kruger, 1995; Stockey, 1998).

So, if environmental policy matches with R&D policy and R&D policy helps firms in their production-oriented R&D investments, then it may be that support to pollution abatement gets enforced through support to privately-performed and growth-promoting R&D. In this way we make a point in favor of the optimistic point of view about sustainable growth.

To tackle the issues outlined above, we explicitly model the distinction between basic research and development in a set up where R&D determines growth and basic research,

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tough accidentally, helps reducing pollution. The framework builds on horizontal innovation literature, with the introduction of the distinction between basic research and development according to both literature and the data.

One of the main result of the model refers to the effects of productivity of research activities on growth and pollution. An increase in basic research productivity helps reducing pollution, whereas an increase in development productivity plays the opposite effect, by reducing the amount of basic research that each innovator needs to have to get a new variety of good, thus reducing pollution abating activity. Overall, the effects on growth are positive, meaning that the positive effect of development productivity in reducing the R&D cost that firms must bear to start producing offsets the negative effect played by the same productivity through pollution.

Failure to internalize both negative externality from pollution and positive spillovers from R&D implies that private agents fail to reach the first best. Therefore, there is room for policy design and welfare discussions with respect to growth, R&D and pollution. To this respect, we will not address the issue of policy-design to reach the first best allocation since it is widely acknowledged that the successful execution of first best policies appears to be difficult (Barro and Sala-I-Martin, 2004). Thus, we will tackle more realistic policy-making through the introduction and the analysis of second-best R&D and environmental policy. We consider a specific environmental R&D policy which is consistent with existing literature on pollution and on R&D: taxes are levied on polluters and revenues are devoted to pollution-abating activities (Smulders and Gradus, 1996). In this set up, the latter activities correspond to R&D activities, so supporting pollution-reducing activities equals supporting production-oriented R&D, a kind of policy which is generally advocated in horizontal-innovation literature. Given this policy structure, second-best optimal fiscal policy shows that the Government must pursue support to basic research as long as applied R&D technology is using basic research at a low level relative to other inputs. This result is deeply related to environmental policy considerations: pollution increases as applied knowledge accumulates, since new final designs correspond to new varieties of intermediate goods, but basic research partly offsets this negative side-effect. So, the optimal fiscal policy result is driven by the fact that any increase in the size of intermediate goods which is not determined by a sufficient employment of pollution-abating basic research does not allow the economy to reach the second best unless the Government intervenes to subsidize basic research usage. Referring to existing literature on growth and pollution, this contribution champions supporting privately-performed basic research, even if basic research, and R&D in general, are not specifically aimed at pollution-abatement. However, it is important to notice that support is due as long as basic research employment is small, whereas every time that the level of basic research is above a critical edge, subsidization is no longer needed.

The paper is organized as follows: Section 2 describes the economy; Section 3 presents the decentralized solution; Section 4 discusses the dynamic optimal taxation problem. Section 5 concludes.

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4.2 The Economy

We model the different R&D components accordingly to previous chapters. With respect to the R&D process, we introduce feedback from development to basic research, a feature which is empirically supported.

The economy is characterized by a unique multi-stage R&D sector: first, firms perform basic research, then basic research output is employed in the second research activity to produce an applied design for a new variety of intermediate good. Intermediate goods are used in the production of the final good forever. Research activities generates spillovers: basic research exerts an inter-sector effect on final good production, whereas development reaches R&D activities, only. The latter assumption comes from the so called "dynamic paradigm", which states that certain basic research processes benefit from feedbacks from applied research and development activities (Stokes, 1997).

Pollution is modelled as a side product of economic activity and it affects the economy as a negative externality on final good production. However, basic research, through its strong and pervasive positive spillover effects, helps reducing the negative effects. The structure of the economy is summarized in Figure 4.2[7].

[7]Upward pointing white arrows show the sequence of processes needed to produce final output. Gray arrows highlight the different purposes of final output. Dotted arrows show the direction of both positive and negative externalities.

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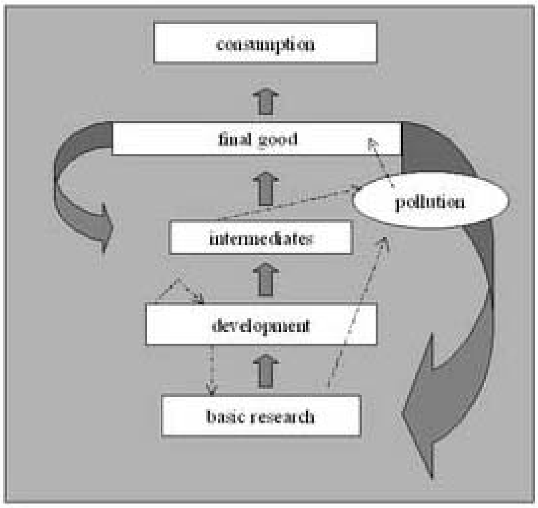

Figure 4.2. The Structure of the Economy

4.2.1 Set up

There are three types of agents in the model. Households maximize utility subject to their budget constraint. They hold shares of intermediate sector firms and they invest in new ideas. Final good producers hire intermediate goods and combine them to produce a final good, which is sold at unit price. This final good serves different purposes: consumption and input for intermediate good production.

R&D firms devote resources to discover new designs through a multi-stage process. We keep assuming that there is uncertainty with respect to exploitability of the final design coming from the manipulation of basic research ideas.

Firms choose whether to enter or not, knowing in advance the characteristics of the economy. All designs and ideas are patented and they are subject to the same law. To this respect, we keep the standard assumption about perpetual patent. The entry game has the

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same structure of the one presented in Chapter 3.

4.2.2 The model

Final good sector. Producers of final good have access to a production technology combining a number of intermediate inputs to produce final output, which is then sold in the market at unit price. Formally,

$$Y = (E_P L_Y)^{1-\alpha} \int_0^N x_j^\alpha dj, \tag{4.1}$$

where $0 < \alpha < 1$. Final good sector uses a continuum of intermediate goods, x_j, and labour, L_Y, as costly inputs and it is affected by an externality, E_P. x_j is the employment of the jth type of intermediate good and N is the total number of varieties of intermediates in the economy. N corresponds also to the total stock of applied designs produced.

Final good is used for consumption and input for the production of intermediate goods. We take the price of Y as the numeraire.

The externality affecting final good production is determined by pollution, exerting a negative effect on workers,

$$E_P = P^{-1} \tag{4.2}$$

Pollution. Following well-established results in economic literature, we assume that natural environment is indirectly a factor of production (Stokey, 1998). Then, natural en-

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vironment is negatively and directly related to pollution. Therefore, we will use the latter as a proxy for natural environment. We adopt the idea that pollution is a side product of economic activity, therefore, we assume that it depends positively on the size of the economy, which we proxy by $\int_0^N x_j^\alpha dj$. Then hinging on both empirical and anecdotal evidence, we also claim that innovation helps reducing pollution and that the strongest contribution to pollution-abatement comes from basic research, being devoted towards general knowledge and not simply focused on new firms creation. Therefore, pollution is determined by the following expression

$$P = \frac{lNx}{Q}, \tag{4.3}$$

where Q represents aggregate basic research ideas.

Intermediate good sector. Each intermediate good producer holds a patent which grants the exclusive right to produce a specific variety of intermediate good. Every patent allowing for a new variety grants perpetual monopolistic profits to producer. We assume that an intermediate good, once invented, costs one unit of Y to produce and it benefits from applied knowledge.

Then, as eq.(4.1) shows, it is used in the production of final good forever.

Research firms. New firms wishing to enter intermediate good production must invest in research first. An entrant has to invest in basic research first and then to use its output as an input to try to get a useful design. This two-stage research process captures both the idea that a basic research design leads to production of goods only if some applied research activity is performed afterwards and that creating breakthrough innovation is not as easy as

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innovating along existing knowledge.

Firms face the two stage decision process typical of standard models of horizontal innovation. First, they decide whether to enter or not. Entrants will invest in R&D if the market value of the firm producing the new variety of intermediate good is at least as large as the R&D expenditure they have to bear to start the firm. Then, they decide the optimal price at which to sell their new intermediate goods to final good sector firms. This price determines the demand they face and, as a consequence, the expected future profits. We solve the two stage problem backward. by deriving the optimal price for new intermediate good, assuming that a new design which translates into a new good has already been invented. Then, we find the value of the firm and compare it to the R&D cost. Since we assume that there is free entry into the business of being an inventor, we will deal with a free entry condition that holds in equilibrium such that entry occurs when the market value of the firm equals the R&D cost. The market values for a new intermediate good firm is given by

$$V = \int_t^{\infty} e^{-\int_t^s r(\tau)d\tau} E_t\pi(s)ds, \tag{4.4}$$

where π are the instantaneous profits from intermediate good production and E_t is the expectation operator, conditional on information at time t. Expected profits at time s as seen from time t from entry are $E_t\pi(s) = l\pi$, since an exploitable design granting perpetual monopolistic profits happens with probability $l, 0 < l < 1$. An intermediate good costs one unit of Y to produce, therefore, profits accruing to firm producing variety j are given by $\pi_j = (\tilde{p}_j - 1)x_j$, where $\tilde{p}_j$ is determined by profit maximization in the final good sector. The

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market values for a new intermediate good firm is given by

$$V = l\frac{\pi}{r}. \tag{4.5}$$

We assume a R&D cost determined by R&D firms profit maximization problems. The R&D cost that entrants must pay corresponds to the price of a new patent. This price is determined by R&D firms considering their two-step technology. The representative firm i generates a new blueprint according to

$$\frac{1}{\eta_N}\left(NL_{Ni}\right)^{\beta} q_i^{1-\beta}, \tag{4.6}$$

where $\frac{1}{\eta_N}$ is an exogenous productivity parameter, L_{Ni} is labour devoted to development activity, q_i is basic research and N is a positive intra-sector spillover effect played by existing applied knowledge. Then, $0 < \beta < 1$.

The same firm i produces basic research, q_i, according to

$$q_i = \frac{1}{\eta_Q} L_{Qi} N \tag{4.7}$$

where η_Q is an exogenous productivity parameter, L_{Qi} is labour force devoted to basic research. Differently from previous chapters, here we are assuming that the stock of applied knowledge exerts a positive externality effect on basic research activity. In other words, we are accounting for feedbacks from development to basic research. At each point in time, there

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are $\dot{N}$ innovators, which we assume to be all equal. Therefore, at the aggregate level, applied knowledge accumulates following $\dot{N} = \frac{1}{\eta_Q^{1-\beta}\eta_N} L_N^{\beta} L_Q^{1-\beta} N$,whereas basic research accumulates according to $\dot{Q} = \frac{1}{\eta_Q} L_Q N$.

Households. Households maximize utility over an infinite horizon. They are endowed with constant aggregate flows of labour which they supply inelastically,

$$\bar{L} = L_Y + L_N + L_Q \tag{4.8}$$

. Their objective function is given by

$$U(C) = \int_0^{\infty} \ln C e^{-\rho t} dt \tag{4.9}$$

Households own shares of intermediate goods firms and receive a wage rate on labour. They discount the future at rate ρ. In a closed economy, the total of households' assets equals the market value of firms and they have to choose between consuming now or accumulating new patents in the two sectors. Their budget constraint is given by

$$C + \dot{a} = w_Q L_Q + w_N L_N + w_Y L_Y + ra,$$

so that the consumption plan they set when maximizing utility subject to the constraints satisfies standard Euler equation

$$\frac{\dot{C}}{C} = r - \rho \tag{4.10}$$

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4.3 Decentralized equilibrium and BGP

4.3.1 BGP

Proposition 4.1 *As long as all R&D activities grow at the same rate, that is* $\frac{\dot{N}}{N} = \frac{\dot{Q}}{Q}$*, then all variables in the economy, including* P*, will grow at the same rate given by*

$$\frac{\dot{N}}{N} = \frac{1}{\eta_Q^{1-\beta}\eta_N} L_N^{\beta} L_Q^{1-\beta} \tag{4.11}$$

Proof. See Appendix A. ■

Now, we need to find the equilibrium expression for this growth rate, therefore, we need to solve for the decentralized equilibrium.

4.3.2 Decentralized equilibrium

Profits from final good production are given by

$$\max_{\{x\}_{j=0}^{lN}, L_Y} (E_P L_Y)^{1-\alpha} \int_0^{lN} x_j^{\alpha} dj, - \int_0^{lN} \tilde{p}_j x_j dj - w_Y L_Y$$

where $\tilde{p}_j$, is the price of the jth monopolized intermediate good. Final good sector is competitive, therefore input prices are taken as given. Also pollution, being an externality, is take as given by firms. Instantaneous profit maximization gives the following first order

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conditions, once symmetry has been imposed

$$\tilde{p} = \left(\frac{L_Y}{P}\right)^{1-\alpha} \alpha x^{\alpha-1}, \tag{4.12}$$

$$w_Y = (1-\alpha) l N x^{\alpha} P^{\alpha-1} L_Y^{-\alpha} \tag{4.13}$$

where we have substituted for E_P using eq.(4.2). Eq.(4.12) is the inverse demand functions faced by intermediate good producers. Recall that we assume that an intermediate good, no matter its type, once invented, costs one unit of Y to produce; this assumption together with the demand functions allow us to write the profit flows for intermediate goods. If we deal with the jth monopolized intermediate good, the profit flow is given by $\pi_j = (\tilde{p} - 1)\, x_j$, where $\tilde{p}$ is given by eq.(4.12). Since monopolists set marginal revenues equal to marginal cost and recalling that $E_P = P^{-1}$, we get that $\tilde{p} = \frac{1}{\alpha}$, $x = \alpha^{\frac{2}{1-\alpha}} P^{-1} L_Y$. Therefore, symmetry across all the monopolized intermediate goods implies that

$$\pi_j = \pi = \left(\frac{1-\alpha}{\alpha}\right) \alpha^{\frac{2}{1-\alpha}} P^{-1} L_Y \tag{4.14}$$

Monopolistic profits represent the positive payoffs from R&D investment, thus providing the right incentive to innovate. Innovation is a costly activity and its cost affects entry decision. This cost has to be determined. R&D evolves following two stages: we may think that the R&D process is carried on by a vertically integrated firm performing both stages. The problem of the typical firm is to maximize instantaneous profits from development activity

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subject to the technological constraint represented by basic research technology, eq.(4.7),

$$\max_{L_{NI},L_{Qi}} \frac{\hat{p}}{\eta_N \eta_Q^{1-\beta}} L_{Ni}^{\beta} L_{Qi}^{1-\beta} N - w_N L_{Ni} - w_Q L_{Qi}$$

where $\hat{p}$ is the price for a new useful design and w_h, $h = N, Q$ is the wage rate for labour devoted to development and basic research respectively. First order conditions and no arbitrage in the labour market imply

$$w_N = \frac{\hat{p}\beta}{\eta_N \eta_Q^{1-\beta}} \left(\frac{L_{Qi}}{L_{Ni}}\right)^{1-\beta} N, \tag{4.15}$$

$$w_Q = \frac{\hat{p}(1-\beta)}{\eta_N \eta_Q^{1-\beta}} \left(\frac{L_{Qi}}{L_{Ni}}\right)^{-\beta} N, \tag{4.16}$$

$$L_{Qi} = \frac{(1-\beta)}{\beta} L_{Ni}. \tag{4.17}$$

Then, as we are assuming that all R&D firms are identical, $L_{Qi} = \frac{L_Q}{\dot{N}}$ and $L_{Ni} = \frac{L_N}{\dot{N}}$. Therefore, we can rewrite the first order conditions and the non arbitrage condition as follows

$$w_N = \frac{\hat{p}\beta}{\eta_N \eta_Q^{1-\beta}} \left(\frac{L_Q}{L_N}\right)^{1-\beta} N, \tag{4.18}$$

$$w_Q = \frac{\hat{p}(1-\beta)}{\eta_N \eta_Q^{1-\beta}} \left(\frac{L_Q}{L_N}\right)^{-\beta} N, \tag{4.19}$$

$$L_Q = \frac{(1-\beta)}{\beta} L_N. \tag{4.20}$$

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Non arbitrage applies also with respect to final good labour market, therefore, we set eq.(4.13), after having substituted for x, equal to eq.(4.18) after having substituted for $\frac{L_Q}{L_N}$ through eq.(4.20)and we solve for the price of a new blueprint

$$\hat{p} = \frac{l(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}\eta_N\eta_Q^{1-\beta}}{(1-\beta)^{(1-\beta)}\beta^{\beta}}P^{-1} \tag{4.21}$$

Eq.(4.21) can be used inside the free entry condition in intermediate good production $r_{entry} = \frac{\pi}{V_N} + \frac{\dot{V}_N}{V_N}$,where π is given by eq.(4.14) and $V_N = \hat{p}$ from free entry. As we are assuming that all variables grow at the same rate along the BGP, $\dot{V}_N = 0$. Using eq.(4.8), (4.20) and eq.(4.21), r_{entry} can be rewritten as

$$r_{entry} = \frac{\alpha(1-\beta)^{(1-\beta)}\beta^{\beta}}{\eta_N\eta_Q^{1-\beta}}\left(\bar{L} - \frac{L_N}{\beta}\right). \tag{4.22}$$

Then, since there is a unique BGP growth rate, the Euler equation generates another expression for the interest rate

$$r_{savings} = \frac{1}{\eta_N\eta_Q^{1-\beta}}L_{Ni}^{\beta}L_{Qi}^{1-\beta} + \rho. \tag{4.23}$$

Non arbitrage in asset market implies that rates of returns must be equal, therefore eq.(4.22) must equal eq.(4.23). Solving for L_N we find

$$L_N = \left[\frac{\alpha(1-\beta)^{(1-\beta)}\beta^{\beta}\bar{L} - \rho\eta_N\eta_Q^{1-\beta}}{1+\alpha}\right]\left(\frac{\beta}{1-\beta}\right)^{1-\beta}. \tag{4.24}$$

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Finally, we substitute the equilibrium expression for L_N inside eq.(4.11) after having substituted for L_Q using eq.(4.20) and we find the equilibrium value for the BGP growth rate

$$\gamma = \frac{\alpha (1-\beta)^{(1-\beta)} \beta^{\beta} \bar{L} - \rho \eta_N \eta_Q^{1-\beta}}{(1+\alpha) \eta_N \eta_Q^{1-\beta}}, \tag{4.25}$$

and for pollution

$$P = \left[\frac{l \alpha^{\frac{2}{1-\alpha}} \eta_Q^{\beta}}{\eta_N} \left(\frac{1-\beta}{\beta} \right)^{\beta} \left(\bar{L} - \frac{L_N}{\beta} \right) \right]^{\frac{1}{2}} \tag{4.26}$$

With respect to eq.(4.25), the following Proposition holds:

Proposition 4.2 *The decentralized outcome given by eq.(4.25) is not Pareto Optimal.*

Proof. See Appendix B. ■

4.3.3 Comparative Statics

Note that the expression for the growth rate is positively affected by the size of population. Then, productivity of basic research plays a positive effect on growth, as well as productivity of development, by increasing returns from R&D investment. With respect to pollution, eq.(4.26) shows that an increase in basic research productivity helps reducing pollution, whereas an increase in development productivity increases pollution, by reducing the amount of basic research that each innovator needs to get a new variety of good, thus lowering the aggregate level of basic research available to abate pollution. Thus, increasing basic research productivity exerts positive effects both on returns from R&D and on pollution abatement, whereas increasing development productivity benefits returns from R&D,

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but increases also pollution. However, since private agents are not able to internalize negative spillovers from pollution, they cannot capture the effects played by R&D components on pollution.

4.4 Environmental Policy

We introduce a Government whose goal is reducing pollution by taxing intermediate good producers and devoting the resulting revenues to basic research support. This policy is consistent to the fact that pollution depends positively on the size of the intermediate good sector and negatively on basic research and also to existing literature on environmental policy and growth (Bovenberg and Smulders, 1995; Stokey, 1998).

Formally, let τ_x be the tax rate on monopolistic profit in intermediate good production and θ_Q be the subsidy rate on basic research. Then, we assume that the Government is constrained to run a balanced budget, which writes as follows

$$\tau_x l N \pi = \theta_Q w_Q L_Q, \tag{4.27}$$

where $0 < \theta_Q < 1$ and $1 > \tau_x > 0$. First, we find the decentralized equilibrium once environmental policy has been adopted and we compare it with to the decentralized outcome without any fiscal policy. In this first exercise, fiscal tools are exogenously given. Then we deal with second-best environmental policy to determined the optimal value for both the tax and the subsidy rate.

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4.4.1 Decentralized Equilibrium

Introducing the environmental policy characterized by the Government balanced budget described in eq.(4.27) causes the following changes: monopolistic profits from intermediate good production are taxed, therefore the value of a new firm in the sector is now given by

$$V_N = \frac{(1-\tau_x)(\tilde{p}-1)\,x}{r_{entry}},$$

where $\tilde{p}$ is still given by eq.(4.12). Then, the Government uses revenues from taxation to help basic research production; as a consequence profit maximization for the $i-$th R&D firm becomes

$$\max_{L_{Ni},L_{Qi}} \frac{\hat{p}}{\eta_N \eta_Q^{1-\beta}} L_{Ni}^{\beta} L_{Qi}^{1-\beta} N - w_N L_{Ni} - (1-\theta_Q)\, w_Z L_{Qi}, \tag{4.28}$$

where we have substituted for q_i in development technology using eq.(4.7). As there are no fiscal tool affecting households, then Euler equation is still given by eq.(4.10).

By going through the same steps highlighted above, we find the decentralized equilibrium and the corresponding BGP growth rate when environmental policy is enforced

$$L_N = \left[\frac{\alpha(1-\beta)^{(1-\beta)}\beta^{\beta}\bar{L} - \rho\eta_N\eta_Q^{1-\beta}(1-\theta)^{\beta}}{(1-\beta\theta_Q)(1+\alpha)}\right]\frac{(1-\theta_Q)\,\beta^{1-\beta}}{(1-\beta)^{1-\beta}}, \tag{4.29}$$

$$\gamma_E = \frac{(1-\theta_Q)^{\beta}\left[\alpha(1-\beta)^{(1-\beta)}\beta^{\beta}\bar{L} - \rho\eta_N\eta_Q^{1-\beta}(1-\theta_Q)^{\beta}\right]}{(1-\beta\theta_Q)(1+\alpha)\,\eta_N\eta_Q^{1-\beta}} \tag{4.30}$$

By comparing eq.(4.29)-(4.30) to eq.(4.24)-(4.25), we can conclude that the introduction of environmental policy has two opposite effects on growth: on the one hand, by diminishing profits from intermediate good production, it reduces the incentive to enter; on the other hand, by subsidizing basic research, it helps pollution abatement but it also benefits profits from intermediate good production. Both effects are present in eq.(4.30).

However, as the positive effect from basic research support is not internalized by private agents, as it affects an externality, we decide to introduce welfare considerations to understand more deeply the consequences of environmental policy. So, θ_Q has to be endogenously determined.

4.4.2 Second-Best Environmental Policy

We have showed that this economy presents a decentralized solution which differs from the first best. Therefore, there is room for fiscal policy. Instead of looking for a fiscal menu pushing the economy towards the first best, here we decide to focus on second-best optimal fiscal policy. This choice hinges on the awareness that successful execution of first best policies appears to be difficult as it generally implies non distortionary tools and the disposal of huge amount of information by policy-makers.

We consider a benevolent Government fixing its distorting environmental policy by taking into account the decentralized competitive equilibrium. In doing so, the Government attempts to internalize both basic research and pollution externalities. To set the second-best environmental policy, the Government chooses θ_Q to maximize eq.(4.9) subject to the decentralized competitive equilibrium. We shall find it useful to rewrite the problem in terms of variables which will be constant in equilibrium, following well-established contributions

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to the second-best optimal taxation theory (Park and Philippopoulos, 2004), therefore, we introduce $\hat{C} \equiv \frac{C}{N}$. The introduction of this variable makes the decentralized equilibrium conditions change as follows

$$\gamma_{\hat{C}} = \frac{\dot{C}}{C} - \frac{\dot{N}}{N} = \frac{\hat{C}}{\hat{p}} - \frac{w\bar{L}}{\hat{p}N} - \rho,$$

where $\frac{\dot{C}}{C} = r - \rho$, with r given by eq.(4.29) and $\frac{\dot{N}}{N} = r + \frac{w\bar{L}}{\hat{p}N} - \frac{\hat{C}}{\hat{p}}$, with w given by eq.(4.13) and $\hat{p}$ given by eq.(4.21). After some substitutions, we get that

$$\gamma_{\hat{C}} = \chi \left[\frac{\zeta - \rho\eta_N \eta_Q^{1-\beta}(1-\theta_Q)^{1-\beta}}{(1+\alpha)(1-\beta)^{(1-\beta)}\beta^{\beta}} \right]^{\frac{1}{2}} (1-\theta_Q)^{\frac{\beta}{2}+\beta-1}\hat{C} - \frac{\phi}{(1-\theta_Q)^{1-\beta}} - \rho, \tag{4.31}$$

where χ, ζ and ϕ are a functions of parameters[8].

Then, the Government has to maximize eq.(4.9) subject to eq.(4.31). The current-value Hamiltonian for this problem is

$$H = \ln \hat{C} + \lambda \left\{ \frac{\chi\hat{C}}{(1-\theta_Q)^{1-\frac{\beta}{2}-\beta}} \left[\frac{\zeta - \rho\eta_N \eta_Q^{1-\beta}(1-\theta_Q)^{1-\beta}}{(1+\alpha)(1-\beta)^{(1-\beta)}\beta^{\beta}} \right]^{\frac{1}{2}} - \frac{\phi}{(1-\theta_Q)^{1-\beta}} - \rho \right\} \hat{C}$$

There is a unique control variable, θ_Z and a unique state variable, $\hat{C}$. First order conditions

[8] $\chi = \frac{(1-\beta)^{(1-\beta)}\beta^{\beta}}{(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}\eta_N \eta_Q^{1-\beta}} \left(\frac{\eta_N}{l\eta_Q^{\beta}\alpha^{\frac{2}{1-\alpha}}} \right)^{\frac{1}{2}}$
$\zeta = (1-\beta)^{(1-\beta)}\beta^{\beta}\bar{L}$
$\phi = \frac{\zeta}{\eta_N \eta_Q^{1-\beta}}$

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for this problem are

$$\frac{1}{\hat{C}\lambda}+\frac{2\chi\hat{C}}{(1-\theta_Q)^{1-\frac{\beta}{2}-\beta}}\left[\frac{\zeta-\rho\eta_N\eta_Q^{1-\beta}(1-\theta_Q)^{1-\beta}}{(1+\alpha)\zeta}\right]^{\frac{1}{2}}-\frac{\phi}{(1-\theta_Q)^{1-\beta}}-\rho=-\frac{\dot{\lambda}}{\lambda}+\rho,$$

$$\frac{2\left(1-\beta\right)\phi\bar{L}}{\chi(1-\theta_Q)^{2-\beta}}=\frac{\left[\frac{(2\beta-1)\rho\eta_N\eta_Q^{1-\beta}(1-\theta_Q)^{2\beta-2}-(3\beta-2)\zeta(1-\theta_Q)^{3\beta-3}}{(1+\alpha)\zeta}\right]\hat{C}}{\left[\frac{\zeta(1-\theta_Q)^{3\beta-2}-\rho\eta_N\eta_Q^{1-\beta}(1-\theta_Q)^{2\beta-1}}{(1+\alpha)\zeta}\right]^{\frac{1}{2}}},\tag{4.32}$$

$$\gamma_{\hat{C}}=\chi\left[\frac{\zeta-\rho\eta_N\eta_Q^{1-\beta}(1-\theta_Q)^{1-\beta}}{(1+\alpha)\zeta}\right]^{\frac{1}{2}}(1-\theta_Q)^{\frac{\beta}{2}+\beta-1}\hat{C}-\frac{\phi}{(1-\theta_Q)^{1-\beta}}-\rho.\tag{4.33}$$

Then, Proposition 1 states that, in equilibrium, all variables grow at the same rate. This finding, together with the definition for $\hat{C}$, implies $\gamma_{\hat{C}}=0$. Using this result inside eq.(4.33) gives the steady state value for $\hat{C}$, which we use inside eq.(4.32) to determine the equilibrium expression for θ_Q[9]

$$1-\Upsilon^{\beta-1}=\theta_Q.\tag{4.34}$$

Then, with respect to eq.(4.34), the following Lemma is verified.

Lemma 4.3 *In an economy described by eq.(4.10)-(4.21), where the Government enforces an environmental policy summarized by eq.(4.27), the second-best policy states that basic research is affected by a fiscal tool given by eq.(4.34) which is positive as long as the amount*

[9] $\Upsilon=\frac{-\Sigma+\sqrt{\Sigma^2+4\Gamma(1-3\beta)\zeta\rho}}{2\Gamma}$
where $\Sigma=\left[(1-3\beta)\zeta\phi+(1-2\beta)-\eta_N\eta_Q^{1-\beta}\rho^2-2(1-\beta)\phi\eta_N\eta_Q^{1-\beta}\rho\right]$
and $\Gamma=\left[2(1-\beta)\phi\zeta+(1-2\beta)\eta_N\eta_Q^{1-\beta}\rho\phi\right]$

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of basic research employed in the R&D process is below a threshold level.

Proof. Eq.(4.34) implies that θ_Q is positive as long as $\beta > 3/5$. Maximization of eq.(4.28) and non arbitrage in the labour market implies the following relationship for labour allocation

$$\frac{L_Q}{L_N} = \frac{(1-\beta)}{\beta(1-\theta_Q)},$$

which shows that, for high value for β, the amount of labour devoted to basic research is low relative to labour devoted to development. Then, according to eq.(4.7), if L_Q is low, then basic research produced is lower and, as a consequence, new designs are produced employing relatively less basic research. Recalling eq.(4.3), we can conclude that any increase in Nx, which is not determined by a sufficient employment of basic research, is not optimal in terms of welfare, as it makes pollution increase too much. ■

Our findings state that environmental policy in this type of economy benefits welfare as long as the R&D process does rely heavily on development activity. In fact, whenever this is the case, as applied knowledge accumulates, pollution increases, since new final designs correspond to new varieties of intermediate goods, while the low employment of basic research does not offset the increase in pollution.

We can conclude that any increase in the size of intermediate goods which is not determined by a sufficient employment of pollution-abating basic research does not allow the economy to reach the second best unless the Government intervenes to subsidize basic research usage.

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Looking at US data on privately performed R&D we find interesting suggestions in terms of policy advice. The share of basic research on total privately performed R&D ranges around 4%, reaching 15% if we assume that a half of applied research is really close to basic research and 23% if we assume that all applied research can be labelled basic research (NSF, 2004). In any case, being the actual share of fundamental research quite small compared to development, our model allows to argue that it would be second-best optimal for US Government to enforce basic research support also with respect to environmental care.

4.5 Conclusion

The debate on the role of pollution on economic growth has, thus far, analyzed the effects of R&D explicitly aimed at environmental care, but little consideration has been given to the effects of the different R&D components. However, basic research is endowed with some peculiarities that may help pollution-abatement even if the R&D process embedding basic research as its preliminary step is not directly aimed at environment preservation. Basic research is, by definition, "a systematic study directed towards greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific application towards procedures and products in mind"; the generality inherent to basic research is such that its output may exert positive effects towards other economic activities through spillovers, which are endowed with the largest span on possible trajectories. Anecdotal evidence has indeed pointed out several trajectories through which basic research discoveries made in some industries such as microelectronics, chemical and manufacturing,

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have been playing some accidental effects on pollution management. Finally, data on US shows a positive magnitude of basic research performed by private agents. All these observations boost to analyze which might be the outcomes of introducing these linkages between R&D, pollution and growth within a growth model.

This paper addresses this issue from a theorethical perspective, by developing an R&D based endogenous-growth model in which pollution is a by-product of economic activity playing a negative effect on final good production, which is partly offset by a positive externality played by basic research. Basic research belongs to a multi-stage research process carried on by private firms for profit reasons, therefore it is not part of pollution-abating R&D.

Within this set up, a unique decentralized equilibrium is found. The decentralized outcome displays different effects of R&D activities: basic research productivity exerts positive influences on growth and pollution, by reducing negative externalities and by increasing private returns from R&D investments; development productivity has more complicated effects, as, on the one hand, it increases the level of pollution in the economy by increasing the amount of goods produced (and therefore pollution) for a given amount of pollution-abating basic research, whereas on the other hand it increases private returns from R&D investment, thus promoting growth.

In terms of welfare and policy design, we find that the decentralized equilibrium is not Pareto optimal: pollution, R&D spillovers and monopolistic competition constitute sources for market failure that private agents fail to internalize. To this respect, instead of focusing on optimal fiscal policy to reach the first best, we decide to tackle second-best optimal

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fiscal policy to deal with fiscal tools which may be more realistically enforced by Governments. The policy we choose to study is both an R&D and an environmental policy, since it provides support to basic research, being an R&D activity generating positive externalities and, at the same time, it helps basic research because it abates pollution. Aid to privately performed basic research comes from taxation to intermediate good producers, as each of them contributes positively to deteriorating environmental quality. Support to basic research is optimal only when the R&D technology usage of basic research relative to other development-specific inputs is below a threshold level. As long as the R&D process does rely heavily on development activity, as applied knowledge accumulates pollution increases, since new final designs correspond to new varieties of intermediate goods, and the low employment of basic research does not offset the increase in pollution. Then, any increase in the size of intermediate goods which is not determined by a sufficient employment of pollution-abating basic research does not allow the economy to reach the second best unless the Government intervenes to subsidize basic research usage. Anyway, support is due as long as basic research employment is small, whereas every time that the level of basic research is above a critical edge, subsidization is no longer needed.

How do this policy advice match with real data? US data on the composition of privately performed R&D shows that the share of basic research on total privately performed R&D is quite small, therefore, we can conclude that it would be second-best optimal for US Government to enforce basic research support also with respect to environmental care.

Solution to second-best environmental policy helps to shed some light on the current

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debate about the effect of pollution concern on economic growth. In fact, our findings states that, if we acknowledge that R&D drives growth and that firms perform basic research, then an environmental policy supporting pollution-abating activities, even if accidentally, and taxing polluters exerts a positive effect on GDP growth as long as basic research activity is relatively smaller than other R&D activities. This result supports the idea that sustainable growth is possible and it is also consistent with empirical evidence on developed countries, where environmental care pursued through policy design does not harm economic growth.

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4.6 Appendix A: Proof of Proposition 1

Eq.(4.1) shows that $\frac{\dot{Y}}{Y} = \frac{\dot{N}}{N}$. Then, we need to show that also consumption and pollution grow at the same rate. We take the economy-wide resource constraint, given by $Y = C + lNx$, and we take the derivative with respect to time. We see that $\frac{\dot{C}}{C} = \frac{\dot{Y}}{Y} = \frac{\dot{N}}{N}$. Then, recall that pollution is given by $P = \frac{lNx}{Q}$, implying $P = \frac{lNx}{q}$, where $q = \frac{1}{\eta_Q}\left(\frac{L_Q}{\dot{N}}\right) N$. So, q will be constant along the BGP. Then, as long as x is constant, as it turns to be in equilibrium, then $\frac{\dot{P}}{P} = \frac{\dot{N}}{N}$. Finally, we can conclude that all the variables in the economy grow at the same rate, given by $\frac{\dot{N}}{N} = \frac{1}{\eta_N \eta_Q^{1-\beta}} L_N^{\beta} L_Q^{1-\beta}$.

4.7 Appendix B: Proof of Proposition 2

The proof to Proposition 2 is given by the solution of the Social Planner problem. The Planner maximizes the utility of the representative household taking into consideration the economy-wide resource constraint and the law of motion for the state variables:

$$\max_{C,x,P,L_Z,L_N} \int_0^{\infty} (\ln C)\, e^{-\rho t} dt,$$

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$$
\begin{aligned}
s.t.\ \dot{N} &= \frac{1}{\eta_N \eta_Q^{1-\beta}} L_Q^{1-\beta} L_N^{\beta} N \\
Y &= C + lNx \\
Y &= \left(\frac{L_Y}{P}\right)^{1-\alpha} lNx^{\alpha} \\
\bar{L} &= L_Q + L_N + L_Y \\
P &= \frac{lNx}{Q} \\
& \quad N_0
\end{aligned}
$$

We write the current value Hamiltonian for this problem as

$$H = \ln C + \mu \frac{L_Q^{1-\beta} L_N^{\beta} N}{\eta_N \eta_Q^{1-\beta}} + \lambda \left[\left(\bar{L} - L_Q - L_N\right)^{1-\alpha} lNx^{\alpha} \left(\frac{1}{\eta_Q^{\beta} \eta_N lx}\right)^{1-\alpha} \left(\frac{L_Q}{L_N}\right)^{\beta 1-\alpha} - C - lNx \right]$$

The relevant FOCs for this problem are

$$C^{-1} = \lambda \tag{4.35}$$

$$\frac{(2\alpha - 1)^{\frac{1}{(1-\alpha)2}}}{\left(\eta_Q^{\beta} \eta_N l\right)^{\frac{1}{2}}} \left(\frac{L_Q}{L_N}\right)^{\frac{\beta}{2}} \left(\bar{L} - L_Q - L_N\right)^{\frac{1}{2}} = x \tag{4.36}$$

$$\lambda \frac{x^{2\alpha-1} \left(\bar{L} - L_Q - L_N\right)^{-\alpha}}{\left(\eta_Q^{\beta} \eta_N\right)^{1-\alpha}} \left(\frac{L_N}{L_Q}\right)^{\beta\alpha} \left[1 - \beta \frac{\left(\bar{L} - L_Q - L_N\right)}{L_Q}\right] = \mu \frac{\beta l^{1-\alpha}}{l \eta_N \eta_Q^{1-\beta} (1-\alpha)} \left(\frac{L_Q}{L_N}\right) \tag{4.37}$$

$$\lambda \frac{x^{2\alpha-1} \left(\bar{L} - L_Q - L_N\right)^{-\alpha}}{\left(\eta_Q^{\beta} \eta_N\right)^{1-\alpha}} \left(\frac{L_N}{L_Q}\right)^{\beta\alpha} \left[1 + \beta \frac{\left(\bar{L} - L_Q - L_N\right)}{L_N}\right] = \mu \frac{\beta l^{1-\alpha}}{l \eta_N \eta_Q^{1-\beta} (1-\alpha)} \tag{4.38}$$

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$$\frac{\lambda}{\mu}\left[\left(\frac{L_Q}{L_N}\right)^{\beta 1-\alpha}\frac{lx^{2\alpha-1}\left(\bar{L}-L_Q-L_N\right)^{1-\alpha}}{\left(\eta_Q^{\beta}\eta_N\right)^{1-\alpha}}-lx\right]+\frac{L_Q^{1-\beta}L_N^{\beta}}{\eta_N\eta_Q^{1-\beta}}=-\frac{\dot{\mu}}{\mu}+\rho \tag{4.39}$$

First, eq.(4.37) implies that $\frac{\dot{\lambda}}{\lambda}=\frac{\dot{\mu}}{\mu}$. Then, using eq.(4.36) inside eq.(4.37) and eq.(4.38) and setting the resulting expressions equal, we get

$$L_Q = L_N$$

which differs from labour allocation in the R&D sector determined by private agents. By substituting this value for labour inside eq.(4.38) and eq.(4.39) and using the resulting expression for eq.(4.38) inside eq.(4.39) we get the equilibrium expression for labour

$$\left[\frac{2\beta\rho\bar{L}}{\eta_Q^{\beta}\eta_N^{\alpha}(2\alpha-1)}-1-2\beta\right]L_N-\frac{4\beta\rho\bar{L}}{\eta_Q^{\beta}\eta_N^{\alpha}(2\alpha-1)}L_N^2+\beta\bar{L}=0$$

This second degree equation in L_N shows that the equilibrium value for labour is unique and different from the decentralized result. We can conclude that the decentralized equilibrium does not match the first best outcomes and that, as a consequence, the growth rate determined by private agents is not Pareto optimal.

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