Innovation-Specific Patent Protection and Growth

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Abstract

In this thesis, I am undertaking the analysis of the effects of increasing intellectual property rights on the reallocation of different kinds of research and development within an endogenous growth framework. This thesis' approach considers the innovation process as sequential and cumulative in nature and studies the effects of different property rights regimes on a country's innovative performance. In particular, by explicitly modelling basic and applied research and development (R&D) within a general equilibrium framework, I try to overtake the existing growth theory, which usually aggregates all sources of R&D and innovation, neglecting intermediate inventive steps. My approach is certainly inspired by the current Schumpeterian growth theory (see Aghion and Howitt, 1998 and 2009), which envisages new products and processes arising from Poisson processes, whose arrival rates depend on private and public R&D. However, unlike the previous Schumpeterian models, in most of the chapters of this thesis, creative destruction itself is modelled as a two-stage processes, or more precisely, as a sequence of investment decisions in R&D, whose result is a probability to invent (basic research) or to innovate (applied research). Hence, the first step, "basic research", creates a research tool which is by itself not profitable, but has the potential to become the basis for the second step innovation. The second step is a marketable product which increases consumers' utility and, through the grant of a patent, generates the monopolistic rent for the second step innovator, i.e. the manufacturer of the new product. This is a natural and simple way to explicitly model basic and applied research, yet it entails non-trivial technical complications in the models along with strong policy implications.

Chapter 2 tries to answer the following research question: in order to foster innovation and growth should basic research be publicly or privately funded? This chapter studies the impact of the shift in the U.S. patent system towards the patentability and commercialization of the basic R&D undertaken by universities. Such a shift rendered the U.S. universities more responsive to "market" forces. Prior to 1980, universities undertook research employing researchers motivated by "curiosity." After 1980, universities patent their research and behave as private firms. This move, in a context of two-stage inventions (basic and applied research) has an a priori ambiguous effect on innovation and welfare. Chapter 2 builds a Schumpeterian model and matches it to the data to evaluate this important turning point.

Chapter 3 extends the model presented by Chapter 2 by introducing Kremer's (1998) mechanism for inducing innovation by means of auctions for new patents. Such patent buy-outs are run by the public sector in order to reward innovators and freely disseminate most of the new basic research findings. My work is the first attempt to use Kremer's idea to address the issue of the patentability of basic research and the financing of early innovation. The same Chapter 3 also quantitatively analyses the impact of the so called "research exemption" of patented basic knowledge. Under the research exemption doctrine, if the second innovator is successful in developing a saleable product or process, then he or she can patent it and yet infringe another patent.

The key question that modern economies' innovation systems have been facing in the past few decades is: how should basic research be funded in view of maximizing the efficiency of the innovation system as a whole? In other words, is it possible to conceive the privatization of a country's basic knowledge and an efficient system of incentives to basic research? The study presented by Chapter 4 provides a quantitative assessment on the effects of the US patent reforms that, at the beginning of the Eighties, brought to the patentability of research tools, often invented by the university-led research activity. In particular, Chapter 4 re-examines the policy scenarios and the comparisons presented throughout Chapter 2 and Chapter 3 in order to try to provide these two with a robust empirical support. In the first scenario, only the public sector institutions undertake basic research, rendering all results publicly available for firms, racing to find patentable applications. In the second scenario, important for assessing the post-1980 reforms in the US system of innovation, basic research itself is privatized, and hence patented by private firms. The most important question for the political economy of basic research is which system is most conducive to innovation and growth. The public system permits more idea dissemination, but may not give basic researchers enough incentives to focus their research on the directions most needed by the private developers downstream. The private system optimally channels basic research, but, by allowing the patentability of ideas upstream, precludes free entry into applied R&D. This generates conflicting effects, and the policy conclusions depend on the value of all the relevant parameters in the economy.

In Chapter 4, I estimated the most important of these parameters with the US data immediately preceding the major reorganization of university and basic research in the 80s, and I simulated the two scenarios. The resulting simulations show that public R&D system, prevailing at that time, was indeed outperforming every privatized alternative scenario.

Since the incentives to conduct basic or applied research play a central role for economic growth, Chapter 5 tries to answer the following research question: how does increasing early innovation appropriability affect basic research, applied research, education, and wage inequality?
Chapter 5 analyses the macroeconomic effects of patent protection by incorporating a two-stage cumulative innovation structure into a quality-ladder growth model with skill acquisition. It focuses on two issues (a) the over-protection vs. the under-protection of intellectual property rights in basic research; (b) the evolution of jurisprudence shaping the bargaining power of the upstream innovators. It shows that the dynamic general equilibrium interactions may seriously mislead the empirical assessment of the growth effects of IPR policy: stronger protection of upstream innovation always looks bad in the short- and possibly medium-run. In a common law system an explicit dynamic macroeconomic analysis is appropriate; hence I have incorporated the mathematical modelling of the evolution of the common law into the rational expectations of the agents. This major modification allows me to schematically replicate the evolution of the skill premium, education, and strengthening of intellectual property rights (IPR) happened in the US during the Eighties and Nineties of the XX century. Chapter 5 also provides a simple "rule of thumb" indicator of the basic researcher bargaining power and 5 shows that IPR evolution can be introduced into a fully rational expectation framework. This helps explaining the well-known dynamics of the skill premium and education in the US, that motivated well-known theories of skill biased technical change and directed technical change (see Acemoglu 2008).

Chapter 6, finally, draws inspiration from an important recent empirical literature on competition and productivity in the service sectors (see Nicoletti and Scarpetta, 2003; Alesina et al., 2005; Griffith et al., 2006; Aghion et al., 2006) to build a theoretical framework to predict whether innovation is hampered by the lack of completion in the non-manufacturing sectors. In this final chapter, I have built a simple model of process innovation where the provision of essential services (intermediate inputs, for example financial services or transports) for the production of the final good is subject to sectorial regulation, which shapes the market structure of the intermediate sector as a non-competitive one. The structure adopted in this chapter allows examining the effects on the economy of the presence of two different monopolized tasks: the intermediate service provision and the use of the innovation. The ultimate purpose is to show how the lack of competition in an intermediate essential sector, like the service sector, is actually able to depress productivity growth in the final sector.

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Statement of Copyright

List of Abbreviations

CRRA	**Constant Relative Risk Aversion**
CRS	**Constant Returns to Scale**
EC	**European Community**
ELR	**Economic Loss Rule**
ENIPerf	**Expenditure in Basic Research Net of the Industry Performed Basic Research**
ENIPerf	**Expenditure in Basic Research Net of the Industry Funded Basic Research**
GDP	**Gross Domestic Product**
ICT	**Information and Communication Technologies**
IP(R)	**Intellectual Property (Rights)**
R&D	**Research and Development**
RHS	**Right Hand Side**
S&E	**Scientist and Engineers**
TFP	**Total Factor Productivity**
TRIPs	**Trade-Related Aspects of Intellectual Property Rights**
US(A)	**United States (of America)**
USPTO	**United States Patents and Trademarks Office**

To Guido

Chapter 1

R&D-Driven Economic Growth and the Incentives to Innovation: Background on the Literature

1.1 Introduction

Technological progress is one of the main sources of economic growth (Helpman, 2004). In this thesis, I will try to show how changes in the patent law (Chapter 2 and Chapter 4), in the system of innovation incentives (Chapter 2 and Chapter 3), and in the court orientation (with a special reference to common law systems - Chapter 5) may affect the long term performance of the economy – particularly focussing on innovation, functional inequality, and education.

The discussion on intellectual property in recent years has mainly focused on the problem of rewarding R&D activity in the framework of sequential innovation according partial equilibrium methodology. A large literature has developed around the idea that innovations are not single cut off discoveries with no relevance in terms of future innovations[1]. However, the importance of integrating the traditional microeconomic approach

[1]Scotchmer (2004) and Hopenhayn, Llobet and Mitchell (2006) provide two recent and optimal sur-

to the economics of innovation with the general equilibrium approach appears more and more evident in the purpose of examining the effects of different innovation policies on market and non-market oriented institutions. In this sense, here I try to give micro-economic foundation to the channels through which the system of innovation incentives operates in generating better or worse performances in terms of both basic and applied research at the macroeconomic level.

Starting in the early Nineties, two main stream of literature, aimed at exploring the linkages between R&D activity, intellectual property and economic performance, developed. Probably motivated by the U.S. loss in technological competitiveness (compared to Europe and Japan) during those years, these two streams tried to incorporate the logic of the oligopolistic patent race literature first invented during the Eighties (see, among the others, Reinganum (1985), Grossman and Shapiro (1986) and (1987)) into two new class of models. One adopted a dynamic general equilibrium approach in order to depict the effects on economic growth of the alternation in time of different monopolistic positions producing (and selling) on the market[2] only the top-quality existing good or service in a given production line, each of these monopolistic position being the result of an endogenous choice to invest in R&D by private entrepreneurs (this was the Schumpeterian growth theory). The second stream of literature explored what type of incentive dominates R&D activity in a contest of sequential and cumulative innovation.

In order to assess the performance of the standard multi-sector Schumpeterian growth model as an analytical tool to perform economic analysis after the introduction of a two-stage uncertain research activity, this chapter briefly introduces the reader to the basic features of the two literatures and suggests a possible route to reconcile them. My aim is to provide a new insight on the link between intellectual property and innovation for the case in which basic research and applied research are performed by heterogeneous agents.

veys on the literature.

[2]It will become more clear in the following as, from the point of view of the intellectual property policy, the fact of a firm producing a good may not necessarily imply the fact the firm itself it is allowed to sell it.

In fact, traditionally basic research findings used to be conceived in public institutions and put into the public domain, thus triggering patent races by freely entering perfectly competitive private R&D firms aiming at inventing a better quality product.

1.2 Technological Progress: From Residual to Leader of the Economic Growth

Macroeconomic growth theory recognizes three fundamental sources for economic growth: the accumulation of physical capital, the building-up of human capital, and the increase in the stock of knowledge and technical progress.

Robert Solow (1956, 1957) analysed the relationship between physical accumulation and income growth. Solow's results stress the mechanism through which the growth rate of income per capita is negatively related to the capital-labor ratio in the economy. Consider, for example, the Cobb-Douglas production function[3]:

$$Y(t) = A(t)K(t)^{\alpha}L(t)^{1-\alpha} \tag{1.1}$$

where the term $A(t)$, known as total factor productivity (TFP), indicates the level of technology[4], and $K(t)$ and $L(t)$ are respectively the physical capital and labor inputs. As usual, the constant $\alpha \in (0,1)$ denotes the capital share over the output. Because of the assumption of constant returns to scale (CRS) and perfect competition the capital share and the labor share sum up to one. After taking the derivative of the logarithm of the previous equation, it is immediate to express the output growth rate as:

$$\frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} + \alpha\frac{\dot{K}}{K} + (1-\alpha)\frac{\dot{L}}{L} \tag{1.2}$$

The growth rate of aggregate output equals, the growth rate of TFP $\frac{\dot{A}}{A}$, plus a weighted

[3]It is straightforward to see how this Cobb-Douglas case satisfies the properties of a neoclassical production function (see, for example, Barro and Sala-i-Martin, 2004, page 30).

[4]Here technology is assumed to be output augmenting.

average of the growth rate of the two inputs, where the weights are the corresponding inputs shares.

The analysis assumes population growing at a constant rate, labor productivity improving at a constant rate, and capital depreciating at a constant rate. Because of these assumptions, without capital accumulation the capital-labor ratio in the economy is meant to decline over time. Hence, the role of investment is to replace the depreciated capital and to further increase the capital stock up to point where the original capital intensity is restored. Technological progress - treated as exogenous in this framework - increases the productivity of workers and thus enlarges the quantity of labor effectively supplied. Two fundamental implications of Solow's analysis are:

1. the growth rate is inversely related to the capital intensity;

2. in the international comparisons countries exhibiting lower capital intensity are predicted to be the fastest growers.

As emphasized by the literature on income convergence, the main trouble with the approach to growth theory based on physical capital accumulation pioneered by Solow arises when one wishes to compare the growth rates across different countries because it does not pass the test to the data (Helpman, 2004). The reason for such a theoretical impasse is explained in the following: poor countries, characterized by a lower capital/labour ratio, are those which have the strongest incentive to accumulate capital and thus poor countries should exhibit larger growth rates. The literature on income growth convergence emphasized how by the end of the Nineteenth century the income growth and living standard of many poor countries dramatically failed to reach the levels of rich and middle-income countries.

A second large literature stressed out the importance of human capital as factor determining the growth of the economy aggregate output. Jorgenson and Griliches (1967) found that a non-negligible fraction of the Solow residual could be explained by changes in the quality of inputs as improvements in the quality of labor force. Borrowing Uzawa's

(1963) approach to "optimal education", Robert Lucas (1988) pioneered an endogenous growth model where the representative consumer decides her time-allocation between supplying labour and educating herself and thus becoming a skilled worker. The higher the level of accumulated skills (i.e. human capital) the individuals have, the higher is the output that they are able to produce. Hence, a higher human capital implies a higher growth rate for the economy. Goldin and Katz (2001) showed that during the twentieth century about a quarter of the U.S. per worker income growth was determined by the increase in the education level. Consistently with these studies on the U.S. economy, Young (1995) results' confirm the relevance of schooling and education for growth for Asian countries. The concern about measuring the contribution of labour to the production by taking into account just the number of hours per worker and not the quality of the labour itself is well expressed in Barro and Sala-i-Martin (2004) words:

> "*. . . If persons with college education have higher wage rates (and are presumably more productive) than persons with high school education, then an extra worker with college education accounts for more output expansion than would an extra worker with a high school education.*
>
> *(...)The overall labor inputs is the weighted sum over all categories, where the weights are the relative wage rates. For a given total of worker hours, the quality of labor force improves – and, hence, the measured labor input increases – if workers shift towards the categories that pay higher wage rates.*" (Barro and Sala-i-Martin (2004), page 437).

Along this thesis, I will focus on a branch of the innovation literature that does not assign to physical capital any role as an engine of growth. The focus on technology has a long tradition, arising from Solow's (1956) model with decreasing returns to capital offset by the linear depreciation of capital: this is well known to imply that capital accumulation (per efficiency unit of labour) only matters along the transition to a steady state, in which only labour augmenting technological progress can guarantee persistent growth.

It is worth noticing that a recent literature exists which re-establishes a role for capital accumulation and growth, by focussing on endogenous growth through investment-specific technological change. In fact, if, as in Huffman (2007) and (2008), one assumes that R&D activity is targeted to increase the productivity of new investment goods, this may render capital accumulation and technological growth complementary, thereby obtaining an important link between investment and growth. Quite interestingly, in this class of models, despite capital being an essential factor of persistent growth, a positive capital tax rate can be optimal, as long as it serves to subsidize research and development.

I will not incorporate R&D aimed at investment-specific technological change in any of my models, but I certainly acknowledge the potential importance of analysing the effects of basic/applied research composition in deepening our understanding of investment-specific innovation.

Since the early 1990s, a large literature on endogenous growth theory focussed on technological progress as the most important factor determining the growth rate of the per-capita output. As highlighted by Elhanan Helpman (2004, page 33), a compelling empirical and theoretical literature exists in favour of the argument that TFP growth - i.e. the residual factor in the Solow's model - plays a central role in explaining the discrepancies in per-capita income across different countries.

Since Robert Solow's (1957) pioneering contribution, the main purpose of growth accounting has been to break down the growth rate of aggregate output into the contributions from the growth of inputs, usually capital and labor, and the growth of technology.

From the equation (1.2), it is possible to express the rate of technological progress $\frac{\dot{A}}{A}$ as a residual:

$$\frac{\dot{A}}{A} = \frac{\dot{Y}}{Y} - \left[\alpha \frac{\dot{K}}{K} + (1-\alpha)\frac{\dot{L}}{L}\right]. \tag{1.3}$$

Hence the Solow residual $\frac{\dot{A}}{A}$ would capture the contribution of technological progress to the aggregate output growth rate as the share non-captured by the inputs growth. For this reason it is usually assumed that Solow residual is the measure of our ignorance about the determinants of output growth rates.

Economic growth scholars have argued whether the Solow residual is the ultimate measure that captures the contribution of technological progress and of knowledge to the advances of the standard of living. Put into different words, they have asked if the overall economic consequences of scientific advance do merely get captured by the technological parameter $\frac{\dot{A}}{A}$. The answer to this question, maybe the fundamental question underlying the last thirty years of research on endogenous economic growth, is "no", or at least "not directly". The reason for that answer will hopefully appear clearer to the reader after that she completed the reading of this chapter. For the moment, let the author anticipate the intuition that the contribution of technological progress and of knowledge to development resides in the quality of the inputs employed in the production of the final output or in the better-quality goods (qualitatively different goods) providing the individuals with more utility compared with the old lower quality goods. Hence, the contribution of knowledge and technological progress is captured not only by the productivity parameter but is also captured and incorporated by a better quality of the inputs employed in the final output production or by better-quality consumption-goods.

Now let us turn to a canonical exposition of the economic growth theory. According to the Solow (1956) and Swan (1956) exogenous growth theory, in order to sustain a positive per-capita output growth rate in the long run, the economy must feature a continuous advance in technological knowledge in the form of new goods, new markets or new process. In fact, in the absence of technological progress, the output growth rate will eventually be driven by the population growth rate and coincides with it. This in turn implies that growth as measured by the rate of increase of output per-person will cease in the long run because of the diminishing returns to capital.

Pre-dated in the 1960s and in the 1970s by a few notable exceptions (later specified), during the mid-1980s a group of economists became increasingly dissatisfied with the exogenously driven explanations of long run productivity growth. This brought to the first attempts to endogenize growth. The fundamental issue of endogenizing technological change was to consider technological progress not as exogenous – and hence as an unexplained event – but as depending on economic decisions by agents at least as much as the decisions about capital accumulation (or education). Hence, the first challenge to the usual general competitive equilibrium appeared. In fact, introducing technological progress – together with physical capital and labor – as a coefficient in the production function of the final output and making it depend on individual choices maximizing an objective function, implies that also this factor of production – together with labor and physical capital – has to be rewarded as any other production input. This in turn generates increasing returns to scale in these three factors whenever the production function exhibits constant returns to scale in capital and labor together, and when the coefficient representing technological progress is held constant. Because of the Euler's theorem, not all factors could be paid at their marginal productivity in the case of increasing returns, which in turn generates the necessity to try another avenue than the traditional theory of competitive equilibrium.

The increasing dissatisfaction about the traditional explanation of long-run productivity growth based on exogenous factors as population growth rate spurred various attempts to solve this problem, often based on important models of the Sixties. Most notably, Kenneth Arrow (1962) introduced the concept of "learning-by-doing" according to which the technological progress derives as an unintended consequence of the experience in producing new capital goods. In order to solve the problem of increasing returns to scale, learning-by-doing is assumed external to the firms, both the producing capital goods firms and the acquiring ones. Technological progress becomes endogenous because an increased saving propensity would affects its time path. However Arrow's (1962) model assumed a constant capital/labor ratio and fixed labor requirements, meaning that the long-run growth is ultimately limited by labor growth.

Karl Shell (1966, 1967 and 1973) built a first growth model in which technological progress is driven by deliberate individual choices motivated by the prospect of monopolistic rents. Shell was well aware of the importance of technological progress as the source of economic growth, in fact he maintained that "*While it is probably incorrect to attribute all the residual (unexplained increase in productivity) to 'technical progress', it is clear that inventive activity contributes importantly to increased productivity.*" (Karl Shell (1973), page 77).

Shell considered technical knowledge as an input into the production function of the three sectors of the economy: consumption, investment and inventive sector. He assumed three routes to spur the inventive activity. The incentive to undertake R&D activity – and hence the flow of new ideas developed into the economy – can derive from government expenditures, in this case the technical knowledge is considered as a pure public good which must therefore be supported by non-market institutions. Otherwise the inventive activity can be financed by monopolistic rents in the production of physical capital goods. Since Shell assumes that there exists no patent system (there is no way to appropriate directly the fruits of inventive activity) inventive activity is pursued by the monopolist in order to lower her production costs in machine-goods production (and, when possible, to raise the rental rate on physical capital). The third route is a mere combination of the two above. In fact Shell (1966, 1967 and 1973) assumes the new ideas produced by the following production function:

$$\dot{A} = \alpha\sigma f(k) - \rho A \tag{1.4}$$

where k is the per worker physical capital, A is the technology index, $\alpha \in [0,1]$ is the fraction of output devoted to invention, $\sigma \in (0,1]$ is the fraction of inventions that are successful, and $\rho > 0$ represents the decay in the technical knowledge reflecting, according to Shell, either the loss to the economy due to the retirement of the technically trained members of the labor force or the imperfect transmission of technical information from one generation of labor force to the next. Shell (1966, 1967 and 1973) assumes a dynamic optimization framework to get to the solution of the model and he shows that, as the time tends to infinity, the two accumulable factors of the economy – physical capital and technical knowledge – tend to constant values.

From the our perspective, Shell's pioneering contribution to economic growth theory was remarkable in its brilliant idea of combining the macroeconomic analysis with the study of non-perfectly competitive market structures allowing the successive economic modelling to envisage ways to incorporate the endogenous technical change into a growth model. As Shell wrote in 1973:

> "*For the most part, in these contemporary growth models of the mixed or enterprise economy, either perfect competition is assumed or the specification of the industrial organization is vague. The Schumpeterian vision of the capitalist development, that the level of inventive activity and in turn growth in productivity are crucially dependent upon the prevailing form of industrial organization, is largely overlooked.*" (Karl Shell (1973) page 77)

Based on Frankel (1962), later attempts to endogenize the long run growth rate conduced to the AK approach, a class of models in which technology is assumed to grow in proportion to capital, and in which this additional element in the production function counteracts the effects of decreasing returns to capital, allowing to output to grow in proportion to capital. The typical production function of this type of models is in fact $Y = AK$, where A is a fixed coefficient representing technological progress, K is the capital stock, and Y is output. It is evident in such a case that the marginal productivity of capital is constant and equal to A.

Romer (1986) and Griliches (1979) emphasized the role of externalities in the process of accumulation of knowledge. In this way, they were able to allow for increasing returns in the model even with firms perceiving themselves as price-takers.

1.3 Vertical *versus* horizontal innovation process

Despite Shell's (1966, 1967 and 1973) influential attempts to introduce endogenous technical change into growth theory, the birth of R&D-based endogenous growth literature is traditionally attributed to the seminal works of Romer (1990) and Segerstrom, Anant and Dinopoulos (1990), subsequently developed in works of Aghion and Howitt (1992, 1998) and Grossman and Helpman (1991a). These works present some important differences. In particular, while Romer (1990) analyses the case in which technological progress takes the form of an ever expanding product variety, Aghion and Howitt (1992) and Grossman and Helpman (1991a) consider technical knowledge arising by the introduction of better qualities of the existing goods.

These are the two principal forms of innovation envisaged by the R&D-based endogenous growth models:

1. horizontal innovation process (Romer, 1990), and
2. vertical innovation process (Aghion and Howitt, 1992, and Grossman and Helpman, 1991a).

The horizontal innovation process consists of an ever expanding product variety ("horizontal") which may be interpreted both as final goods and as intermediate inputs for the production of the final output.

The vertical innovation process is so defined because new ideas get incorporated into better-quality versions of the existing goods, in the form of either a new good which provides a higher quality service or in the form of a new production process for the same good. In this case growth is generated by a random sequence of quality improving innovations ("vertical") – resulting from uncertain research activities – on the existing goods which can be produced at a lower cost providing the same quality service of the actual vintage. "Leapfrogging" is the metaphor used to describe this type of technological progress, as well as the so called quality ladder for each good.

The main difference between these two forms of innovation resides in the substitutability relation with the existing goods. In fact, horizontal and vertical innovation processes are distinguishable on the basis of the elasticity of substitution between the new vintage and the existing goods (see for example Grossman and Helpman, 1991b ch.3-4). Since the vertical innovation process consists in the developing of better versions of the existing goods, there exists a high degree of substitutability between the actual vintage of a good in a sector and the next one introduced in the same sector. The horizontal innovation process consists instead in the introduction of a completely new good which has a lower elasticity of substitution with the actual vintage; in fact with the horizontal innovation process a new sector is created beside the existing sectors, whereas with the vertical innovation the newly invented good replaces a good in the same sector. In order to better explain this distinction consider Grossman and Helpman's (1991, ch.3 pag.43) words:

> "*industrial research may be aimed at reducing the cost of producing known commodities (process innovation) or at inventing entirely new commodities (product innovation). We may further distinguish product innovation according to whether new invented goods bear a vertical or horizontal relation to existing products. That is, innovative products may perform similar functions to those performed by existing goods, but provider grater quality, or they may serve new functions, thereby expanding variety in consumption or specialization in production.*"

Hence with the vertical innovation process better goods or services are introduced. They will respond to same needs and perform similar functions with the existing goods. Then, the goods characterized by different vintages in the same sector will have a high level of the elasticity of substitution between them, at limit an infinite elasticity of substitution. On the contrary, the horizontal innovation process consists of introducing goods and services which perform completely new functions, new sectors are created beside the existing ones, in the words of Barro and Sala-i-Martin (2004, ch.7 pages 342-343):

> "*...we assumed that the new varieties were no direct substitutes or complements of the existing types; innovation did not tend to drive out the old varieties (...). In contrast, when a good or technique is improved, the new good or methods tend to displace the old one. That is, it is natural to model different quality grades for a good of a given type as close substitute.*"

Romer (1990) and Grossman and Helpman (1991b) assume that R&D consists of introducing completely new varieties of goods and services (either as intermediate or final goods) which have an unitary elasticity of substitution among one another. Segerstrom, Anant and Dinopoulos (1990), Grossman and Helpman (1991a), Aghion and Howitt (1992) assume that the R&D process aims at introducing better-quality versions of existing final or intermediate goods; each new good has an infinite elasticity of substitution with the pre-existing goods: this reintroduces the Schumpeter's (1913, 1934, 1939) "creative destruction" concept.

Different substitutability relations between new and existing goods entail major consequences in the contest of the R&D-based growth literature. In fact, as remarked above, within a vertical innovation framework each new product occurs with its industry and so it aims at downsize the market share of the old vintage within the same sector. This happens because the new product incorporates the new knowledge through a better quality compared to the existing good, it brings a higher utility to the consumer or it has a lower production cost. Instead, within a context of horizontal innovation each introduction of new goods does not push any of the existing products out of the market, but whenever a new sector is created, it will downsize the market share of each of the existing sectors.

Every "horizontal innovator" looks for a niche of unsatisfied consumer/producer necessities. Hence succeeding in the R&D race does not require the inventor to incorporate all the existing techniques of production in the new good, because there does not emerge the necessity to enter at a lower cost of production (this is because of the low elasticity of substitution with the existing goods)[5].

The present digression on the R&D-based growth literature refers to the seminal paper by Romer (1990) for the analysis of technological progress consisting in an ever expanding product variety, while it considers Aghion and Howitt (1992)'s model as a benchmark for the analysis of technological progress consisting in the introduction of

[5] Pietro Peretto (1998) and Peter Howitt (1999) assume that the newly created sectors enter into the market with a productivity parameter which is drawn randomly from the distribution of the existing industries and hence it will be the average productivity level.

always better qualities of the existing goods.

1.3.1 R&D models with horizontal innovation

This section considers Paul Romer's (1990) model as it is explained by the Aghion and Howitt (1998, chapter 1).

Romer (1990)'s model examines an economy which is made up of three sectors: a final output sector (competitive), an intermediate goods sector (monopolistic competition) and a research sector (competitive). Following Shell's intuition of exploring the potential of non-perfectly competitive market structures for endogenizing the technological progress, Romer (1990) borrows the product variety theory of Dixit and Stiglitz (1977) and introduces monopolistic competition in the intermediate sector. Deliberate R&D activity is performed by firms aiming at generating new knowledge rewarded from monopoly rents on successful innovation. Hence, knowledge accumulation derives from intentional individual choices, spurred by monopolistic rents providing the incentive to undertake R&D activity.

The economy is populated by infinitely-lived individuals who derives utility from consuming the homogenous final good and inelastically supply labor.

The total labor force, L, is employed either in manufacturing the final output (L_Y) or in research (L_R). Hence the following constraint on the labor employment must be verified:

$$L = L_Y + L_R \tag{1.5}$$

Final Output Sector

The final sector produces a homogenous final good Y, capable to be utilized either for consumption or as an input for the differentiated intermediate goods i:

$$Y = L_Y^{1-\alpha} \int_0^N x(i)^{\alpha} \, di \qquad \text{with } 0 < \alpha < 1. \tag{1.6}$$

In a symmetric equilibrium $x(i) \equiv x$ and (1.6) becomes:

$$Y = L_Y^{1-\alpha} N x^{\alpha}. \tag{1.7}$$

Each firm in the competitive final output sector takes prices as given in the profit maximization problem:

$$\max \pi_Y = L_Y^{1-\alpha} \int_0^N x\,(i)^{\alpha}\, di - wL_Y - \int_0^N p\,(i)\, x\,(i)\, di \tag{1.8}$$

where the final good as been chosen as numeraire, $p_Y = 1$, w is the wage rate, and $p\,(i)$ is the price of $x\,(i)$.

The first order conditions determine the inverse demand functions:

$$p\,(i) = \alpha L_Y^{1-\alpha} x\,(i)^{\alpha-1} \qquad \forall i \in [0, N] \tag{1.9}$$

and

$$w = (1-\alpha) L_Y^{-\alpha} \int_0^N x\,(i)^{\alpha}\, di. \tag{1.10}$$

Intermediate Goods Sector

Let δ denote an exogenous productivity parameter. The following equation is key to Romer (1990)'s model as it represents the research technology, i.e. the way in which the R&D firms produce new economically valuable ideas by combing labor[6] and the differentiated capital goods:

$$\dot{N} = \delta N L_R. \tag{1.11}$$

[6] In the present exposition, the distinction between unskilled labour and skilled labour (human capital) - present in Romer's (1990) model - is dropped because it is not essential for the results (see also Gancia and Zilibotti, 2005).

From the previous equation it is immediate to notice that the number of blueprints created in the economy per unit time, is directly proportional to the number of researchers and to knowledge accumulated over time, here represented by the number of the existing product lines.

As a technical (and legal) requisite for production, each intermediate firm must purchase the right to utilize the (patented) blueprint (sunk cost). In equilibrium, the patent holder decides its production level to maximize its profit, $\pi(i) = p(i)\,x(i) - x(i)$, subject to equations (1.9) and (1.10).

The optimal price that will be chosen by the monopolist is therefore determined as:

$$p(i) = \frac{1}{\alpha} \tag{1.12}$$

and the quantity produced as:

$$x(i) = \alpha^{\frac{2}{1-\alpha}} L_Y, \tag{1.13}$$

hence the maximum profit for an intermediate firm is given by:

$$\pi(i) = \frac{1-\alpha}{\alpha} \alpha^{\frac{2}{1-\alpha}} L_Y. \tag{1.14}$$

In a steady-state the growth rate of output g is equal to the growth rate of technology.

Hence

$$g = \delta L_R. \tag{1.15}$$

Equations (1.12), (1.13), and (1.15), together with the steady-state Euler equation (where r is the interest rate, ρ the subjective discount factor, and $\frac{1}{\sigma}$ is the intertemporal elasticity of substitution of a constant relative risk aversion (CRRA) utility function):

$$g = \frac{r-\rho}{\sigma}$$

can be solved for the steady-state growth rate of the economy is given by:

$$g = \frac{\alpha\delta L - \rho}{\alpha + \sigma}. \tag{1.16}$$

From equation (1.16) it is immediate to notice how the long-run growth rate positively depends on the population size (scale effect), that is a greater population size (i.e. a greater number of researchers in the economy) implies a greater number of new intermediate goods and hence a higher per capita growth rate.

It is important to remark that, according to Romer's (1990) analysis, technological progress is the result of the intentional actions taken by profit-maximizing individuals. This is why Romer's (1990) model deserves to merit (among the others) of having introduced endogenous technical change deriving from the deliberate decisions of individuals who respond to market incentives.

1.3.2 R&D models with Vertical Innovation

According to Romer's (1990) theory of horizontal innovation, whenever a new variety is introduced a new intermediate or final sector immediately arises, and hence a monopolistic firm which will produce that good. Every intermediate (or final) monopolist[7] will last forever because there is no trace of any kind of obsolescence of old intermediate inputs or final goods and because the legal pant life is assumed to be infinite. The R&D models with vertical innovation try to microfound firm exit by introducing the Schumpeterian concept of "creative destruction" as a fundamental characteristic of the technological progress occurring within a capitalistic economy.

In Grossman and Helpman (1991a) and Aghion and Howitt's (1992) works the first departure from Romer's (1990) article is in fact the appropriate consideration given to the concept of obsolescence, as here the introduction of better products renders the previous ones obsolete.

[7] See Grossman and Helpman (1991b).

This section considers a multisector version of Aghion and Howitt's (1998, chapter 3) model, where the analysis of each intermediate sector coincides with the Aghion and Howitt's (1992) model. The economy is populated by a continuous mass of individuals with identical intertemporally additive preferences. There exists a perfect capital market and each individual is endowed of a one unit flow of labor.

There exist two important categories of labor: unskilled and skilled. The former type can be only employed into the production of the final consumption good, while skilled labor can be used either in research or in the intermediate sector. There is one final good which can only be consumed and which is produced by a continuum of intermediate goods, indexed on the unit interval. Each intermediate good is produced using labor on one-for-one technology and each intermediate good can be used to produce the final output independently of the other intermediate goods, there no exists complementarity between them. Furthermore each intermediate sector is monopolized by the patent-holder of the latest generation of that good; in fact each intermediate firm produces a good protected by an infinitely-lived patent. The intermediate producer could either be thought of as being the latest innovator on that sector (who then set up a new intermediate firm), or an existing intermediate firm that purchases the patent for the innovation from the latest innovator. In either case the latest innovator is able to extract the whole net present value of monopoly profits generated by that innovation during the lifetime of this innovation.

Each intermediate input is able to produce the final output according to the following production function[8]:

$$Y_{it} = A_{it} x_{it}^{\alpha} \tag{1.17}$$

where A_{it} represents the productivity of the latest generation of intermediate good i, and $0 < \alpha < 1$. Aggregate output of the final good is thus expressed by the integral:

[8] The reader should be aware that in this specification of the production function is implicit the normalization to one of a fixed production factor (land or unskilled labour), so that the production function exhibit constant returns to scale.

$$Y_t = \int_0^1 Y_{it} di. \tag{1.18}$$

The local monopolist sells its output to the competitive final good sector at a price equal to the marginal product of the intermediate input x_{it}, that is $p_{it} = A_{it}\alpha x_{it}^{\alpha-1}$. Thus, the monopolist's output and demand for labor (because of the one-for-one technology into manufacturing sector) will be:

$$x_{it} = \tilde{x}\left(\frac{w_t}{A_{it}}\right) = \left(\frac{w_t}{\alpha^2 A_{it}}\right)^{\frac{1}{\alpha-1}}, \tag{1.19}$$

where w_t is the wage rate measured in consumption goods.

The monopolist's equilibrium profit will be:

$$\pi_{it} = p_{it}\tilde{x}\left(\frac{w_t}{A_{it}}\right) - w_t\tilde{x}\left(\frac{w_t}{A_{it}}\right) = A_{it}\frac{1-\alpha}{\alpha}\frac{w_t}{A_{it}}\tilde{x}\left(\frac{w_t}{A_{it}}\right). \tag{1.20}$$

Noteworthy is the negative relationship between both demand for labor and profits with the productivity-adjusted wage rate. As we shall see later, this is an effect which adds to the creative destruction effect determining a negative relationship between current and future research.

Aghion and Howitt (1992, 1998) represent the flow of new ideas, and hence the output growth rate as:

$$\dot{A}_t^{\max} = A_t^{\max}\lambda n \ln\gamma,\ \gamma > 1. \tag{1.21}$$

As in Romer (1990) the flow of new ideas is proportional to the number of researchers. The arrival rate of the Poisson process λ describes the instantaneous arrival rate of innovations, hence λn is the Poisson arrival rate of innovations to the economy as a whole representing the creative destruction effect due to the next innovations and hence depending on the number n of researchers existing in the economy[9]. $A_t^{\max}$ is the leading-

[9] The Poisson process are assumed independent, and independent Poisson processes are additive. This

edge technological parameter, i.e. the productivity parameter in the last innovating sector, and measures the increment of the technology parameter in the final production function and represent the increases of the logarithm of the final output.

The scale effect is evident in the model: a greater population size determines a greater number of researchers and hence a higher flow of new ideas per unit of time. There exist linear spillovers between the stock of knowledge accumulated in the economy until time t and the flow of new ideas; at t each discovery is implementable only in the innovator's chosen sector, but its discovery allows the next innovator to discover a marginally better technique in another sector, by adding to the general knowledge used by that innovator. Because we are in a multisector economy and each new idea is not developed simultaneously in all the intermediate sectors there will be a distribution of productivity parameters across the sector of the economy, with values ranging from 1 to ∞. Aghion and Howitt (1998, ch.3) assume that the shape of the distribution does not need to change: over time the distribution will be displaced rightward as innovating sectors move and as technological progress raises itself, then over time only the name of the sectors occupying different places in the distribution will change. Moreover Aghion and Howitt (1998, ch.3) consider the long-run cross-industry distribution of the relative productivity parameters which does not change over time. Then it is convenient to classify sectors not by their index but by their relative productivity. Let us define the relative productivity parameters a_{it} as $a_{it} \equiv \frac{A_{it}}{A_t^{\max}}$. In the long run, the cross-imdustry distribution of a_{it} will be given by the distribution function:

$$H(a) = a^{\frac{1}{\ln \gamma}}, \; 0 < a \leq 1.$$

We are able to rewrite the monopolist's output and labor-demand for a sector with

means that if there exists a sequence of independent Poisson processes with the same arrival rate then the expected number of arrivals per unit of time is the same parameter λ, the Poisson arrival rate of innovations in the whole economy will be expressed as the parameter λ time the number of researchers in the whole economy n, and the total flow of arrivals is measured by the canonical Poisson distribution.

relative productivity a_{it} at the date t as:

$$\tilde{x}\left(\frac{\omega_t}{a}\right) = \left(\frac{\omega_t}{\alpha^2 a}\right)^{\frac{1}{\alpha-1}}, \tag{1.22}$$

where $\omega_t = \frac{w_t}{A_t^{\max}}$ is the productivity-adjusted wage rate paid to skilled workers employed in the manufacturing sector.

The aggregate demand for labor can be found multiplying this demand by the density of such sectors $h(a) \equiv H'(a)$ and summing over $0 < a \leq 1$. The labor-market clearing condition $L = n_t + \int_0^1 \tilde{x}\left(\frac{\omega_t}{a}\right) h(a)da$ determines the productivity-adjusted wage rate in terms of the mass of research workers.

Classifying the sectors by their relative productivities, it is possible to express the aggregate final output production function as:

$$Y_t = A_t^{\max} \int_0^1 a\tilde{x}\left(\frac{\omega_t}{a}\right)^{\alpha} h(a)da \tag{1.23}$$

where $h(a)$ denotes the density of the relative productivity parameter distribution. Considering that population is held constant over time and hence the manufacturing labor force is a constant fraction of the population, it follows that the instantaneous growth rate of aggregate output at each date will be the growth rate of the leading-edge parameter $A_t^{\max}$ as indicated by the above spillover equation.

Creative destruction

As mentioned above, the new element introduced by the seminal work by Aghion and Howitt (1992) regards the Schumpeterian creative destruction concept which characterizes the capitalistic process incorporated into a benchmark model of general equilibrium with vertical innovations. The creative destruction consists of 'destroying' the economic rents of the incumbent through the introduction of either a new product or a new production process which allows producing at a lower cost. This in turn on one side determines the destruction of the economic rents of the incumbent, and on the other side contributes to the technological progress creating better products for the consumer and creating better opportunities for the whole economy because of the advances in the technological frontier.

In virtually all Schumpeterian growth models it is predicted that the incumbent innovator chooses not to do any research: all research is conducted by outside research firms/individuals – which are attracted by the prospect of the monopolistic flow rents for a successful innovation – rather than the incumbent monopolist. The incumbent does not conduct research because it would internalize its monopoly right's obsolescence and therefore would subtract its current value from the payoff of a successful innovation. This implies that the value to the incumbent innovator of making the next innovation is strictly less than the value to an outside researcher: this is an example of the Arrow effect or replacement effect (see Tirole, 1988).

The innovation process is random because the new ideas arrive according to a Poisson process, but the relationship between the amounts of research in two successive periods is defined as deterministic. In particular there exists a negative relationship between research efforts of two successive periods, more research next period discourages current research through at least two effects.

The first effect is creative destruction: the incentive to undertake research this period depends on the payoff of the successive periods, wich is on the future expected monopolistic rents. These rents will last until the next successful innovator will displace the incumbent introducing a better quality of the good, and at that time the knowledge underlying the rents of the incumbent will be rendered obsolete. Hence more research next period means a higher probability to be soon replaced by the next innovation – through the assumption of a positive (usually linear) relationship between the number of researchers and the flow of new ideas per unit of time – discouraging current R&D activity due the reduction of the rents flow.

The second effect works through the wage paid to skilled labor. In fact in this model it is assumed the existence of skilled labor which may be employed either in manufacturing or in research. The expectation of more research next period determines a greater expected demand for skilled labor thereby increasing the future real wage rate of skilled labor and hence reducing the monopolistic flow rents that will be gained after the introduction of a better quality of good: this in turn discourages current research. The model shows the existence of unique steady-state equilibrium and also the possibility of cyclical growth patterns.

Considering a multisector economy – that is an economy in which there exists several, at the limit infinite, intermediate inputs to produce a unique final output (see Aghion and Howitt, 1998, chapter 3) – there exists another important effect that discourages the current research, the "crowding out" effect. This effect arises because innovations are continually arriving somewhere in the economy determining a continual wage rise, this in turn implies a reduction of employment and profits in the non-innovating sectors.

These considerations may well be summarized by the following formulation of the present expected value of an innovation in the steady state:

$$\omega_t = \frac{\lambda V_t}{A_t^{\max}} = \frac{\lambda \frac{1-\alpha}{\alpha} \tilde{x}(\omega_t)}{r + \lambda n + \frac{\alpha}{1-\alpha} \lambda n \ln \gamma} \tag{1.24}$$

where V_t is the discounted expected payoff of an innovation. This equation represents a fundamental relationship in the model: the arbitrage condition between manufacturing and research activity. The skilled labor force can be employed either in the manufacturing sector or in the research sector, then the arbitrage equation allows to have a positive amount of skilled worker in the both sectors. The numerator of the RHS is the profit flow earned by the monopolistic producer of the latest innovation of an intermediate good, the negative dependence of the profit flow on productivity-adjusted wage rate is evident from this expression where the skilled labor employed in the manufacturing sector with the most advanced technology $\tilde{x}(\omega_t)$ is a decreasing function of the productivity-adjusted wage rate. The term λn represents the next period's research effort (in the steady state each time the number of researchers will be constant and equal to n) and hence the probability flow to be displaced by the next innovator. Thus future research discourages current research by reducing the discounted expected payoff of an innovation. Again r is the interest rate and the last term $\frac{\alpha}{1-\alpha}\lambda n \ln \gamma$ represents the crowding out effect.

From a normative point of view Aghion and Howitt (1992 and 1998) consider both intertemporal spillover and appropriability effects, which generate a less than optimal growth rate in Romer's (1990) model, but they consider another effect that works in the opposite direction. In Aghion and Howitt's (1992 and 1998) models the average growth rate may be too low or too high than the welfare maximizing level. There exist positive externalities represented by the intertemporal and inter-industry spillovers whereby the knowledge embedded in each innovation can be used by all future researchers, and by the appropriability effect, whereby the monopoly rents from an innovations cannot be totally appropriated by the successful innovator (they can appropriate only a fraction of the output, i.e. the fraction of equilibrium revenue in the intermediate sector accruing to the monopolist), and the remaining part of these rents are appropriated by the consumer as surplus. The third effect which operates in the opposite direction is the so called business-stealing effect familiar to the patent-race literature (Tirole, 1988). Each successful innovator does not consider the destruction of the incumbent rents when she introduces a better quality of the existing intermediate input. When the size of innovation is fixed, the business-stealing effect could lead to too much innovations in the economy because it dominates the other two positive effects.

The same conclusions are obtained by Grossman and Helpman (1991b, chapter 4), who state that in a decentralized economy the incentives for R&D may be more or less than optimal.

Grossman and Helpman (1991b, chapter 3) find that when R&D aims at introducing completely new products lines the market incentives for product developments always are insufficient when industrial research generates technological spillovers. The different conclusions are due to the above external effects: a positive spillover for consumers of innovative products, who obtain greater services after any new innovation; a second external benefit due the knowledge spillover to latest innovators, and a negative spillover due the business-stealing effect. Hence also the welfare analysis put in evidence the fundamental distinction between vertical and horizontal innovation process. Indeed the business stealing effect takes place because of the high substitutability between the existing goods and the new ones. The introduction of a new good replaces the actual vintage of the same good and then destroys the monopolistic rents of the incumbent, this in turn could generate too much innovations. Conversely, the horizontal innovation process introducing new varieties of goods – which have a low degree of substitution with the existing varieties – will show a lower business-stealing effect (in the measure of the reduced market share for each good) which will be dominated by the above positive externalities.

1.4 The Scale Effect

The first strand of Schumpeterian growth models was plagued by the so called scale effect on per-capita output growth rate: not only do the research efforts affect per-capita output growth rate but a higher aggregate research effort in the form of a higher number of researchers engaged into R&D activity generates a higher per-capita output growth rate. The prediction that skill acquisition affect the per capita output growth rate was not new at the time of Schumpeterian growth literature, in fact Lucas (1988) – inspired by Becker's (1964) theory of human capital – sustained that human capital accumulation rate drives growth in the economy, so differences in the growth rates across countries are mainly attributable to differences into rates at which those countries accumulate human capital over time. This depends on the specification of human capital as an input in the final output production function, just like any other production input; it follows that the output growth rate depends on the growth rate of human capital. Differently, Nelson and Phelps (1966) maintained that growth rate is driven by the stock of human capital accumulated in an economy, thus cross-country differences in the growth rate depends on the different stock of human capital existing in each country, and most importantly, a country's ability to innovate or to catch up with more advanced countries depends on the human capital stock existing and on the past educational attainment. In this case human capital – as incorporated in the labor force – is the primary source of innovations. Thus the growth rate of output will depend on the rate of innovation and hence on the level, rather than the accumulation rate, of human capital.

Turning to the first strand of Schumpeterian models of economic growth these models predicted at least three important consequences for long-run economic growth. First, larger economies should grow faster; second, population growth over time determines an accelerating per-capita income growth rate, and third, changes in inputs used in knowledge creation – and hence policies that influence these variables – should be accompanied by changes in the growth rate.

An influential paper by Charles Jones (1995a) put forward an important empirical critique to the endogenous growth literature, both in the AK-type models of endogenous growth, and in the R&D-based growth models. In fact, the AK model predicts that a permanent increases in the investment rate generates a permanent increases in the GDP growth rate, while the R&D-based growth models predict that increases in the research effort in the economy generate permanent increases in the per-capita output growth rate. The scale effect prediction consists in the ties between the research effort and per-capita output growth rate, which means that per-capita GDP growth rate is almost proportional to the population size, hence a greater population size would determine a higher per-capita GDP growth rate, an economy with growing population would show an explosive growth rate.

Jones' (1995a,b) critique is based on two empirical works showing how the growth rates of per-capita GDP has shown little or no persistence increases in the post-World War II era of OECD countries. Then whatever endogenous growth models predict that permanent movements in some variable (investment rate or population size and hence number of researchers) have permanent effects on per-capita GDP growth rate, then either the same variable must exhibit no large persistent movements or some other variable must offset these movements; this last hypothesis is considered unlikely by Jones (1995a) who state "*. . . either nothing in the U.S. experience since 1880 has had a large, persistent effect on growth rate, or whatever persistent effect have occurred have miraculously been offsetting.*"

The data described by Jones (1995a) indicate that for some OECD countries the investment rates have increased substantially in the post-world war II period, and the producer durable investment rates too; this strong trend with a high probability could not be offset by any other variable influencing the growth rate – as human capital and openness – which both certainly have shown for the same period an upward trend. Moreover from Jones' (1995a) analysis appears that a permanent increase in the investment rate has no permanent effect on per-capita GPD growth rate, but also that the horizon over which the increased investment rate generates its effects on the growth rate is short, it is on the order of five-eight years.

More drastic conclusions are reached referring to R&D-based growth models, in particular for the first strand of Schumpeterian growth models (Romer, 1990; Grossman and Helpman, 1991a; Aghion and Howitt, 1992). The time series evidence shows how the number of scientists and engineers engaged in R&D in France, Germany and Japan since 1965, and the same variable in the United States since 1950, have dramatically increased at least up to 1987. Jones (1995a) shows how the same trend emerges if we refer to the real R&D expenditure. Total factor productivity (TFP) growth data show negative trends for France and Japan and no distinct trend for U.S. and Germany. This in turn implies that the conclusions of the first strand of R&D-based growth models – the scale effect on growth existing in Romer (1990), Aghion and Howitt (1992), Grossman and Helpman (1991a) models – are at odds with the data.

The same conclusions are obtained if we consider that technological progress is driven by a constant share of labor force devoted to R&D. In fact Jones (1995b) shows how this share had strongly positive trend in the U.S. in the post-war period, passing from about 0.25% in 1950 to nearly 0.80% by 1988. The evidence is similar for France, Germany and Japan.

Moreover, the first strand of R&D-based growth models has an additional important conclusion which is radically changed with the alternative analysis by Jones (1995a, b). Eliminating the prediction of scale effects induces a return to the Solow-like implications for long run growth: long run per-capita growth depends on parameters that are considered exogenous and consequently whichever policy changes, such as subsidies to R&D or subsidies to capital accumulation, produce no effects on the per-capita output growth rate.

The empirical analysis conducted by Jones (1995a, b) spurred a second strand of Schumpeterian growth models aiming to eliminate the scale effect prediction and to restore a role both to the endogenous technological progress for long run growth of an economy and to government policies influencing the pace of knowledge accumulation and hence per-capita output growth rate.

Jones' contributions also motivated further empirical evidence in this field. Kocherlakota and Yi (1997) construct a simple model in which long-run growth depends positively on public capital and negatively on distortionary taxation. Their analysis refer to the U.S. and United Kingdom data and shows how government investment stimulates growth but the budget constraint requires raising taxes offsetting growth effects, that is their effects are almost exactly offset, a very difficult case as argued by Jones (1995a, b).

Several studies also investigated the existence of scale effects at the industry level, i.e. as the result of the industry evolution. The empirical evidence is not uniform on the validity of Gibrat's Law, but all of these studies point in the direction of no scale effects at the level of firm. Other two important studies respectively by Jovanovic and MacDonald (1994), and Klepper (1996) have suggested that the scale effect may underlie factors that generates industry shake-outs.

In conclusion the empirical evidence about scale effects in the Schumpeterian growth models shows that growth rates have accelerated over the course of a century or more, but they have failed to accelerate in the face of increasing R&D effort during the last forty years.

Moreover, the empirical evidence provided by Jones (1995a, b) has been subject to a different critique, this time based on some measurement problem associated with the output growth rate and with the measure of the increasing quality of goods and services. Aghion and Howitt (1998, ch.12 Appendix) consider at least four major problems for the measure of the knowledge-based growth models. These may be summarized as:

- Knowledge-input problem: this considers many workers which are employed in production, management, or other non-research activities. In this case these workers spend a lot of time looking for better ways of producing and selling the output of the firm for which they work, this time and effort should be considered as part of the cost of creating knowledge.

- Knowledge-investment problem: the product of formal and informal R&D activities is typically not well measured at all because it does not result in an immediate commodity with a market price. That is the output of knowledge often produces his payoff not instantaneously or at least not in the same productive cycle, then its effect on GNP may be counted with a certain delay.

- Quality-improvement problem: the product of the research activity often consists of better qualities of goods and services, there exist several difficulties constructing price indexes that account for quality improvements especially in the service sector where the same output presents measurement problems per-se; this in turn implies that much of the resulting benefit goes unmeasured.

- Obsolescence problem: the standard measure of GNP ought to include a separate investment account for the production of knowledge in order to account for the depreciation of the stock of knowledge that takes place as it becomes obsolete being superseded by new discoveries and innovations. Moreover, the creation of new knowledge creates the depreciation of existing physical and human capital, and these problems become more and more acute when a wave of innovations accelerates the obsolescence rate.

Up to now we have considered the scale effect on the per capita output growth rate. However it is not the only scale effect which result from several Schumpeterian growth models. Jones (1999) shows that changes in research intensity positively affect the long run level of per capita income along a balanced growth path, whereas Howitt (1999) show that population size negatively affects the level of per capita income. Differently to the scale effects on per capita output growth rate, there exists no empirical evidence on the scale effects which operates on the level of per capita income. Moreover in any model in which the steady state per capita output depends on the population growth rate, there exists a sort of once-over scale effect on the steady state growth rate engendered by an increase of population growth rate.

In order to show the routes used to purge the scale effects from the first strand of Schumpeterian growth models we follow Dinopoulos and Thompson's (1999) account. Let the final output be obtained according to the following production function:

$$Y(t) = A(t)\, L_Y(t) \tag{1.25}$$

where $Y(t)$ is output, $L_Y(t)$ is the labor force devoted to the final good production and $A(t)$ denotes the state of technology at time t.

The output growth rate evolves over time following the advances in the technological frontier whose specification depends on the type of R&D assumed, vertical or horizontal.

The first type of models (Segerstrom and Dinopoulos, 1990; Grossman and Helpman, 1991a; Aghion and Howitt, 1992) assume that $A(t) = \lambda^{q(t)}$ where $\lambda > 1$ (is equal to one plus the quality increment of a good relative to its immediate predecessor in an industry), and $q(t)$ is the number of innovations that have occurred since time zero.

The models with horizontal innovation (Romer, 1990; Grossman and Helpman, 1991b) assume that $A(t) = N(t)^{\frac{1}{\sigma-1}}$ where $N(t)$ is the number of varieties active at time t and $\sigma > 0$ is the elasticity of substitution between goods.

The technological frontier evolves according to

$$\frac{\dot{A}(t)}{A(t)} = \gamma I(t) \tag{1.26}$$

where $\gamma = \frac{1}{\sigma - 1}$ in the variety expansion class of models, and $\gamma = \ln \lambda$ in the quality ladder models. $I(t)$ represents the effective R&D investment, i.e. the number of innovations per unit of time $\dot{q}(t) = I(t)$. A general relationship which describes the scale effects generated from this first strand of Schumpeterian growth literature may be written down as

$$I(t) = \frac{L_A(t)}{X(t)}, \tag{1.27}$$

where $L_A(t)$ is type labor force engaged into research activity; the interpretation give to the term $X(t)$ is the key to remove the scale effect. Let us proceed by combining the equations (1.26) and (1.27) as follows:

$$\frac{\dot{A}(t)}{A(t)} = \gamma \frac{L_A(t)}{X(t)} = \gamma \frac{L_A(t)}{L(t)} \frac{L(t)}{X(t)}. \tag{1.28}$$

Because of the symmetry hypothesis and because in steady-state the fraction of labor force employed into R&D has to be constant, the removal of the scale effects requires that the steady-state growth rate of the term $X(t)$ be exactly the same as the population growth rate.

From equation (1.28) it is evident that routes followed to eliminate the scale effects coincide with the term $X(t)$ with an economic meaning.

One route introduced the concept of increasing complexity into R&D activities, which is the idea that research becomes more and more difficult over time because the most obvious ideas are discovered first (see Jones, 1995b, Kortum, 1997, and Segerstrom, 1998 for examples of this way out of the scale effects). In such a case $X(t)$ is a R&D difficulty index that evolves according to a simple dynamic formulation capturing the idea that the most obvious discoveries are obtained first.

A second route appended the horizontal innovation process to the vertical R&D activity. Such type of models considers both types of innovations (Young, 1998; Aghion and Howitt, 1998, ch.12; Dinopoulos and Thompson, 1998; Peretto, 1998; Peretto and Smulders, 1998; Howitt, 1999). In this case $X(t)$ represents the number of sectors existing in the economy at time; the scale effect is eliminated through the dilution effect because the economy wide R&D is diffused over a greater number of varieties in larger economies. As population grows over time completely new product lines are introduced into economy at the same population growth rate, the flow of new sectors per unit of time and population grow at the same rate, at least in the steady state. It follows that the increasing size of researchers is spread over the increasing flow of new sectors, leaving the per-sector vertical R&D effort unchanged.

Both approaches generate a steady state in which there only exists scale effect on the level of per-capita output, but not on growth rate.

The increasing complexity argument generates the so-called exogenous Schumpeterian growth models in which long-run per capita income growth is proportional to the rate of population growth rate and hence the policies by the government does not produce any long-run effect. The second route gives origin to the endogenous Schumpeterian growth models in which the per-capita output growth rate depends both on population growth rate and on a term that may be affected by a variety of permanent policy changes.

The third way adopted in the literature to purge the Schumpeterian growth model from the strong scale effect was developed by Cozzi (2003) and Cozzi and Spinesi (2004). The argument is simple: one should be able to identify a theory which is independent from any assumption on the difficulty index $X(t)$. The authors state that in order to invent new or better products it is necessary to invest a fraction of the researchers population into an updating activity aimed on the last relevant innovations introduced in the economy. Hence the updating activity subtracts flow labour time from the pure inventive activity. Let the time spent on updating be denoted by the constant $\mu \in [0, 1]$, it is possible to express the evolution of the economy-wide technology as:

$$\dot{A}(t) = \gamma A(t) L_A(t) \left(1 - \mu \frac{\dot{A}(t)}{A(t)}\right), \tag{1.29}$$

where γ captures the R&D productivity; $\frac{\mu}{A(t)}$ is a positive flow labour unit cost of keeping oneself updated about the latest innovations. Crucial is the idea that in order to try to bring a technology improvement in the sector in which a researcher operates, he or she must devote $\frac{\mu}{A(t)} > 0$ to acquire the latest technology improvements. From equation (1.29) it is immediate to notice that the higher is the already accumulated general knowledge, the lower the updating cost is. This captures the effect of the ICT or general purpose technologies in facilitating the information transmission across the economy. Solving (1.29) for $\frac{\dot{A}(t)}{A(t)}$ yields:

$$\frac{\dot{A}(t)}{A(t)} = \frac{1}{\frac{1}{\gamma L_A(t)} + \mu} = \frac{\gamma L_A(t)}{1 + \mu\gamma L_A(t)}. \tag{1.30}$$

Hence the growth rate of knowledge is bounded by a constant value:

$$g_A = \frac{\dot{A}(t)}{A(t)} < \frac{1}{\mu}.$$

Moreover, from (1.30) we notice that the growth rate of technology (and hence of the per-capita output) is an increasing function of the amount of labour allocated to R&D, $L_A(t)$, but exhibit strongly decreasing returns to R&D everywhere, being strictly concave and bounded by $\frac{1}{\mu}$ from above.

From equation (1.30) it is possible to see that if population tends to infinity, the per-capita output growth would tend to infinity if and only if:

$$\frac{\dot{A}(t)}{A(t)} = \frac{1}{\frac{1}{\gamma L_A(t)} + \mu} = \frac{\gamma L_A(t)}{1 + \mu\gamma L_A(t)} \to \infty, \tag{1.31}$$

which implies:

$$\frac{1}{\gamma L_A(t)} + \mu \to 0,$$

which is possible if and only if $\mu \to 0$. Hence, the per-capita growth is explosive if and only if the in the long rung the researchers do not spend a fraction of their time in getting updated.

The updating cost productivity adjustment approach can be generalized to include the case of decreasing returns to ideas. Following Jones (1995), let $\varphi\left[A\left(t\right)\right] = \gamma A\left(t\right)^{\phi}$, with $0 < \phi < 1$. With this new ingredient equation (1.30) becomes:

$$\frac{\dot{A}\left(t\right)}{A\left(t\right)} = \frac{1}{\frac{A(t)^{1-\phi}}{\gamma L_A(t)} + \mu}. \tag{1.32}$$

Cozzi (2003) shows that, provided that the growth rate of the population is not too high, the relationship between the output growth rate and the population growth rate is increasing as in Jones (1995), otherwise, for relatively high population growth rates, the balanced growth rate of the per-capita output becomes identical to the case of constant or increasing returns to R&D, i.e. $\frac{1}{\mu}$.

In-House and Outside Innovation: Two Influential Papers

Two influential papers considered innovations from a different point of view: innovations are conducted either by larger and larger incumbent firms or by new firms, in the former case we have in-house innovation and in the last case outside innovation. In particular we refer to the influential works respectively by Peretto (1998) and Howitt (1999). Peretto (1998) uses the dilution argument to eliminate the scale effect, but the distinctive element of his work that makes it worthy to treat, even albeit briefly, is the industrial structure analysis conducted by the author.

Peretto (1998) assumed that the existing firms incur fixed costs in order to reduce marginal costs and increase product quality, moreover new firms incur fixed costs in order to bring new varieties to the market. The key aspect is that firms set up R&D facilities and accumulate proprietary knowledge in order to reduce costs, offer lower price, and expand sales. In this set up, increasing returns to innovations are internal to the firm. With permanent increases in the population growth rate the economy converges to a steady state in which productivity growth rate is the same as before the permanent population growth rate change, but in which firm size is larger and entry is faster. Hence the author considers the case in which vertical R&D is conducted by larger and larger incumbent firms. This depends on the assumption of increasing returns to scale internal to the firm whereby the scale of the economy matters because it influences the scale of production of an individual firm. As a firm produces more, it applies its knowledge over a larger volume of output and the rate of return to R&D increases; this implies that an economy with larger firms grows faster because firms run larger R&D programs. The forward looking expectations allow firms to anticipate that a larger economy attracts entry of new firms producing new varieties and this exactly offsets the effect of a larger market on the returns to innovation.

These arguments together determine the steady state productivity growth rate and firm size. The firm size however will be larger for countries with a higher population growth rate, i.e. for countries where population grows faster. The above argument implies that steady-state firm size is increasing (linearly in the model) in the population growth rate, this is because entry of new firms is costly and requires time. Hence in countries where population grows faster – i.e. have a higher population growth rate – there is at any moment in time a larger influxes of workers that find their employment in the existing firms. Hence the key aspect of Peretto's (1998a, b) models resides not only in the elimination of the scale effect through the dilution argument, used in many other papers, but in the industrial structure in which R&D in conducted by larger and larger incumbent firms.

Peter Howitt's (1999) analysis incorporates both the increasing complexity and dilution arguments.

Consumption and R&D are both produced under perfect competition by a continuum of intermediate products. Total output of the economy at any date is

$$Y_t = C_t + N_{vt} + N_{ht} = \int_0^{Q_t} A_{it} x_{it}^{\alpha} di \tag{1.33}$$

where C_t is consumption, N_{vt} and N_{ht} are respectively vertical and horizontal R&D expenditures, Q_t is the number of sectors existing at time t, x_{it} is the flow of intermediate product i, A_{it} is the productivity parameter attached to the latest version of the intermediate product i. Each intermediate product is produced by a monopolistic firm using labor with a one-for-one technology, hence the total cost of each intermediate incumbent will be x_{it} and the price will be $p_{it} = A_{it} \alpha x_{it}^{\alpha-1}$. Considering the relative productivity distribution $F(a) = a_{it}^{\frac{1}{\ln \gamma}}$, where $a_{it} = \frac{A_{it}}{A_t^{\max}}$, profit maximization implies that each local monopolist supplies the quantity $\tilde{x}\left(\frac{\omega_t}{A_{it}}\right) = \left(\frac{\omega_t}{\alpha^2 A_{it}}\right)^{\frac{1}{\alpha-1}}$.

In the vertical innovation process Howitt (1999) envisages the increasing complexity argument in order to prevent growth from exploding as the amount of available capital as an input to R&D grows without bound. In the horizontal innovation process the author assumes that variety-creation depends on resources devoted to horizontal innovations and on final output through a constant returns to scale production function, and there is free entry in varieties. The most important novelty regards the different ability of the potential R&D workers; in fact Howitt (1999) assumes the existence of an unchanging cross-sectional distribution of horizontal R&D ability, and only the best ones are allocated to the introduction of new product lines – i.e. have the Schumpeterian 'entrepreneurial ability' – since there exist no quality differences among workers engaged in either manufacturing or vertical R&D. Hence Howitt (1999) assumes an exogenous distribution of entrepreneurial abilities among the population.

Howitt (1999) eliminates the scale effect through the assumption that what is really important for the advances in the technological frontier is the per-sector research effort; he assumes that knowledge spillovers produced by vertical innovations have to consider the impact on the stock of public knowledge, the greater the public knowledge stock the smaller the marginal impact of a new innovation on the aggregate economy. This in turn allows to only considering the role of the per-sector research effort to spur technological advances.

This reasoning is well summarized by the differential equation describing the growth of the leading-edge technology $A_t^{\max}$:

$$g = \frac{\dot{A}_t^{\max}}{A_t^{\max}} = Q_t \lambda n_t \frac{\ln \gamma}{Q_t} = \ln \gamma \lambda n_t \tag{1.34}$$

where λn_t is the Poisson arrival rate of vertical innovations for each sector (n_t is the productivity-adjusted expenditure on vertical R&D in each sector), hence the term $Q_t \lambda n_t$ represents the economy-wide Poisson arrival rate of vertical innovations. The term $\frac{\ln \gamma}{Q_t}$ measures the marginal impact of each innovation on the stock of public knowledge as said above, this implies that advances in the technological frontier depend on the per-sector research effort. The theoretical argument against the scale effect is based both on dilution arguments and on the spillover arguments. Indeed when population grows over time completely new varieties are introduced into the economy at the same growth rate, this leaves the productivity-adjusted per-sector research effort unchanged. But what allows to eliminate the scale effect is also the always decreasing marginal impact on the whole economy of the vertical research spillover, which decreases as the number of sectors (and hence population size) rises.

In Howitt (1999) the absolute value of the research spillover, i.e. the term $\ln \gamma \lambda n_t$, remains constant over time, but the marginal impact of the latest innovations on the stock of public knowledge tends to decrease as the number of new sectors grows over time. At the same time there will be more and more sectors which are active in vertical R&D and from which the research spillover operates. Then on the one side the marginal impact of the latest innovations decreases over time and to the other side this spillover operates in an increasing number of sectors, because these two opposite effects depend on the number of product lines they cancel out respectively causing the productivity-adjusted research effort per sector – and hence to productivity growth rate – to remain unchanged.

Horizontal R&D is driven by a concave, constant-returns production function with positive marginal products, which, expressed in intensive form, is given by:

$$\dot{Q} = \frac{\psi\left(h_t\right)}{A_t^{\max}} \tag{1.35}$$

where $h_t = \frac{N_{ht}}{Y_t}$ is the fraction of GDP allocated to horizontal R&D. Howitt (1999) introduces the assumption that R&D expenditures (both vertical and horizontal) are subsidized at the proportional rate, then the marginal cost of both vertical and horizontal R&D is $1-\beta$. In this case the two arbitrage equation for both vertical and horizontal R&D can be written down as:

$$\frac{\lambda V_t}{A_t^{\max}} = 1-\beta = \psi'\left(h\right)\Gamma^{-1}\frac{V_t}{A_t^{\max}}. \tag{1.36}$$

where V_t is the discounted expected payoff of an innovation and $\Gamma^{-1} = E(a)^{\frac{1}{1-\alpha}}$ is the long run expected value of the invariant distribution of the relative productivity parameter. The first equality represents the arbitrage condition for vertical R&D, while the equality between the first and the last term represents the arbitrage condition for horizontal R&D.

Considering the second equality we are able to obtain the constant fraction of GDP allocated to horizontal R&D:

$$\psi'\left(h\right) = \lambda\Gamma. \tag{1.37}$$

In the steady state per-capita output can be written as:

$$\frac{Y}{L} = y = A_t^{\max}\Gamma^{\alpha-1}\left(\frac{L}{Q}\right)^{\alpha-1} \tag{1.38}$$

In the steady state the amount of labor per product line $l = \frac{L}{Q}$ is assumed constant – i.e. population and the flow of new sectors per unit of time grow at the same rate – so that population growth creates no continual scale effects through demand channel. Then the per-capita output growth rate depends on the flow of new ideas developed for the introduction of better versions of the existing goods. Equation (1.34) shows that the growth rate of output per person depends on the number of per-sector vertical R&D. The potential supply-side scale effect of a raising number of R&D workers is nullified by the rise in the number of product lines, which reduces the spillover coefficient $\frac{\sigma}{Q_t}$. This means that the scale effect is eliminated not only through the dilution argument – a higher number of researchers spread over a higher number of sectors whereby the per-sector research effort remains unchanged– but also by the fact that a higher number of products reduces the marginal contributions of the inter-industry spillover, in fact as Howitt (1999) maintains: "*an innovation of a given size with respect to any given product will have a smaller impact on the aggregate economy.*"

The fundamental consequence of this line of reasoning is that an economy with more sectors could produce as many innovations as an economy with only one sector. Hence an economy with only one sector could grow at the same pace as larger economy with more sectors, which is admittedly questionable. However the aim by Howitt (1999) was to show how the long run growth rate of output per-person is determined by the same forces as in the original model by Aghion and Howitt (1992, 1998) but is increased by a subsidy to R&D, moreover there exists an additional positive effect of the growth rate of population, not its level.

1.5 Knowledge: appropriation and dissemination

The peculiar character of public good of knowledge and information is recognized throughout the economic literature. Like any public good knowledge is non-rivalrous – its possession by one party does not naturally exclude its possession by another party (Arrow, 1962) – and non-excludible, at least once it is made public. Moreover, the incremental cost of an additional user is virtually zero and, unlike the case with other public goods, not only is the stock of knowledge not diminished by extensive use, but it is often enlarged.

The character of public good of the knowledge is particular because it is often possible to exclude other individuals from its use; a typical form of legally protected exclusion is the institutions of patents, copyrights, etc. It is noteworthy to underline that not all the information incorporated in patents or in other forms of legal protection of the information – as well as the information made public through the commercialization of the products or through the codification of the productive process – are sufficient to reveal all the relevant knowledge.

The exclusive practice of knowledge is so naturally assumed that in the recent years a completely new paradigm emerged in competitive strategies that identifies the primary role of firms to be that of generating rents form sourcing, creating, replicating, integrating and commercializing knowledge (Liebeskind, 1997). This means that knowledge is the primary and fundamental source of economic rents and competitive advantage of individuals and firms in the economy, and this in turn implies a great effort – both formally legal and informal – aiming to protect and to exclude other individuals or firms from own knowledge. The Schumpeterian growth models usually assume a typical form of information protection, patents, which on one hand confers the market power to produce in exclusive way a good – obtaining monopolistic rents which give the economic incentive to undertake R&D – and on the other hand allow to diffuse the knowledge incorporated into the patent throughout the whole economy. Hence the peculiar character of knowledge as a public good is that it is highly valuable for any individual and firm when it is privately kept. This in turn implies a high incentive to produce this knowledge goods – i.e. the classical problem of scarce incentive to produce public good is at least highly mitigated – and to exclude others from its possession.

Developing knowledge takes time, effort, and manpower, moreover it is an uncertain process, involving both search and luck. Hence one individual or firm has always an incentive to acquire other's knowledge if it can reduce her costs by so doing. This reasoning raises the appropriability question: is the inventor provided with the right incentive to protect and transfer her own knowledge in order to obtain rents from it without incurring into the risk that somebody else expropriates its innovation even before it is made public?

1.5.1 Knowledge appropriation

Knowledge appropriation is an important requirement of the appropriation of the monopolistic rent flows by the innovator through patent grants. The Schumpeterian growth literature considers the knowledge appropriation problem assuming that the patent system confers to the winner of a patent race – that is to the researcher or the firm who obtains the patent from its own invention – a monopoly power on the production of the good for which the patent is granted, or at least the right to sell the patent in the market at a price corresponding to the monopolistic rent flow obtained from the exclusive use of the patent. This in turn implies that the Schumpeterian growth literature does not consider some peculiar characteristics of knowledge, particularly those tied to the dissemination and appropriation of the information before it is legally protected, or at least the fact that not all the knowledge may be legally appropriated by the possessor.

On one hand, all the knowledge disseminated throughout the economy by the mechanism based on patent system refers to codified knowledge, and it does not consider tacit knowledge. Tacit knowledge is not codified and can only learned by observation or by doing (Liebeskind, 1997), furthermore tacit knowledge is deeply rooted in an individual's actions and experience, as well as in the ideas, values or emotions she embraces. Hence the endogenous growth literature should consider this form of knowledge as well, as it appears to be particularly important in dealing with the appropriability problems connected the dissemination of knowledge throughout the economy.

Moreover, there exist other non-market-based mechanisms to reward knowledge and to solve the appropriation problem. Shell (1973, page 78), treating the objection to the capital-theoretic view of technical knowledge, maintained that "*While in life we can find two pieces of machinery that are essentially alike, if two inventions are very alike they are indeed the same invention. Possession of the first invention is enough; virtually* *nothing is gained by possession of a second scrap of paper describing an already known invention*." The most appealing attribute of a reward system that is rooted in priority is that it offers non-market-based incentives for producing the public good knowledge. But how and when is it possible to attribute the priority of an innovation? The innovation has a compounded nature, it is a social activity, it is the result of a set of information and knowledge accumulated over time by each individual and derives from both introspective and human relationship activity. As shown by Cozzi (2001 and 2003) and Rajan and Zingales (2000), innovation – and hence the incorporated knowledge – is a socialised activity, moreover each invention is a compounded "object", that it is a set of different information, it is a result of a problem solving activity, it is the result of the knowledge accumulated throughout the external and internal environment of an individual.

Any single individual who interacts with others in the period in which she is developing new ideas may be expropriated, or at least may disseminate her information and knowledge before to be recognized being as the first at introducing that innovation. The priority system is based on the assumption that each individual who make an innovation is publicly recognized as the mother of that innovation, hence the priority system does not consider the moment before an innovation is made public. It is possible that an individual could be expropriated of her own ideas, again not completed as innovation, before the moment in which it is made public, either formally or informally. This means that the priority system does not resolve the appropriability problem, while the existence of more trusty and conscious social norms and beliefs may instead contribute to create a favourable environment to develop ideas and to diffuse knowledge.

Hence it is possible that not only each inventor could be unable to appropriate her own inventions because of the particular character of knowledge, as described above (public good and not always legally protected), but that the behaviour of each researcher is influenced by the cultural environment and from her internal inclination and nature. This in turn implies that the social environment, the social norms and beliefs, have an enormous role for the behaviour of the researchers on the expropriation of the others' knowledge and information. Moreover the existence of certain social norms and beliefs – such as those based on more trust and confidence and on more awareness of the importance of knowledge as a public good to be supplied in the interest of all – could spur a more effective legal system aiming to spur the innovations. This in turn implies that the human capital accumulated in the schools (see Cozzi, 1998) and in the working environment plays a crucial role in spurring technological progress – not only as in the traditional capital view, and hence as a production factor like the physical capital – but also as the basis of the creation of social norms and beliefs that influence the day-by-day behaviour of the people. This arguments are valid not only in market relationships, that is between single individuals, but can be extended to the behaviour among organized structures, and to relationship within institutions like firms.

The existence of more trusty and conscious social norms and beliefs are fundamental for a better functioning of the knowledge appropriation mechanism – legal and informal – and hence are at the core of the knowledge creation and dissemination. Beside the problem arising from the difficulty to attribute the priority of an innovation before it is made public – a certain type of social norms and beliefs which improve and create a trusty and cooperative environment may give an environment highly favourable to develop innovations and ideas (see Cozzi, 2008).

1.5.2 Knowledge dissemination

The Schumpeterian growth models usually assume that new innovations are disseminated throughout the economy thanks to patents granted to the inventors, i.e. the individuals who win the patent race. Patent law grants patents for inventions that are useful, non-obvious, and novel, that is under a well-functioning patent system one gets the patent only if she proves to have been the first to invent something that her peers typically could not straightforwardly invent, given their actual skills. The patent would add new useful, novel, and non-obvious knowledge to the whole economy and the researchers.

Because in the theoretical models the monopolistic rents are due to an infinitely lived patent system, the important point about this literature regards not the legal patent duration – usually assumed infinite – but its effective life, which will usually be finite with probability one, because a patent will last until the next better good will be introduced.

Before analysing the knowledge dissemination mechanism we shall briefly treat the legal system of intellectual property rights. Assuming a dynamic framework closer to the Schumpeterian paradigm in which innovations are sequential and cumulative – and hence where each innovator is both an initial innovator and a second generation innovator – the prospective on legal system of intellectual protection rights must address not only how to transfer profit to initial innovators but also how to increase profit for each innovator. This in turn implies that in a dynamic innovation framework what is also important for a patent system is the protection against future innovators, not only to ensure a large profit flow to the current innovator, because she could be soon replaced by the next patent-holder. This is a legal consequence of the creative destruction introduced by the vertical innovation process and it is strictly tied to Arrow's replacement effect, at least in the first strand of Schumpeterian growth models.

The literature on patent systems considers – in addition to patent life – at least three tools of patent design: patentability requirements, leading breadth, and lagging breadth. Patentability requirement consists of a minimum threshold innovation size required to receive a patent and it is usually determined by the interpretation of the statutory requirements of novelty, utility, and non-obviousness. The breadth of a patent is defined as the degree of vertical or horizontal differentiation which a new product must satisfy vis-à-vis an existing patented product in order to avoid infringement of the patent. Hence a patent breadth specifies a set of products that no other firm can produce without permission from the patent-holder (in the form of a licensing agreement). Lagging breadth specifies a set of inferior products (i.e. products that require no further innovation) that would infringe a patent, whereas leading breadth specifies a set of superior products (i.e. products that require further innovation) that would infringe the patent. Hence while lagging breadth puts restrictions on imitators, leading breadth and patentability requirement put restrictions on future innovators. O'Donoghue and Zweimuller (1998) try to merge the patent-design literature and the endogenous growth literature in a general equilibrium framework. Usually the patent-design literature adopts a partial equilibrium analysis where stronger patents imply increased profits for successful firms (see, among the others, Chang, 1995; Gilbert and Shapiro, 1990; Green and Schotchmer, 1995; Klemperer, 1990; Van Dijk, 1996). Adopting a general equilibrium framework, O'Donoghue and Zweimuller (1998) find two important differences: on one hand the increased profits imply higher aggregate income and therefore increased demand for all industries, which increase profits further; on the other hand the fact that multiple industries use patents can imply that output distortions created by patents are small. They identify a role for patents in providing protection against future innovators, in particular both patentability requirement and leading breadth could influence the characteristics of new products, or the types of cost reduction that firms pursue and could counteract the tendencies of sub-optimally small innovations.

As said above, on the one hand the patent system gives the incentive to undertake R&D activity due the monopolistic rents accruing to the patent-holder, and on the other hand the patents reveal the knowledge incorporated into new innovations. Knowledge dissemination and appropriation is allowed from the patent system. The information revelation mechanism based on the patent system generates the knowledge spillovers which allows to researchers to make further advances in the technological frontier.

General knowledge accumulation is the result of all adoption efforts (side effect) plus direct general knowledge production (by public R&D, foundation sponsored R&D, universities, etc.). It is usually assumed that the advances in general knowledge in a sector spills over to the other sectors, i.e. it is an economy-wide general knowledge. This economy-wide spillover is usually assumed instantaneous and it does not require researchers any waste of time or effort to absorb the new advances of the technological frontier. This allows each researcher and the economy in general to increase the technological frontier by introducing always better quality products along the quality ladder, adapting the new knowledge of the latest patents to their own sector, or by introducing completely new product lines as in Romer (1990). Borrowing from Aghion and Howitt's (1998, Chapter 3) and Howitt's (1999) idea of intersectoral spillover it is essential to realize that is a state variable that summarizes all economy-wide technological information: hence the whole distribution of vertical productivities across sectors and the number of active sectors. Therefore technological frontier summarizes the knowledge accumulated in the whole economy. Hence as Romer (1990, pages S83-S84) maintains:

> "*The second is that the larger the total stock of design and knowledge is, the higher the productivity of an engineer working in the research sector will be. According to this specification, a college-educated engineer working today and one working 100 years ago have the same human capital, which is measured in terms of years of forgone participation in the labor market. The engineer working today is more productive because he or she can take advantage of all the additional knowledge accumulated as design problems were solved during the last 100 years.*"

Moreover in Grossman and Helpman's (1991b, ch.3 pag.57) words:

> "*... each research project contributes to a stock of general knowledge capital. This capital stock represents a collection of ideas and methods that will be useful to later generations of innovators. It may include components such as scientific properties of particular materials, the chemical formulas for certain compounds, or the structure of new computer algorithms.*"

These considerations mean that knowledge spillovers are fundamental for the creation of new ideas, each researcher who wants to introduce either a better version of the existing goods or a completely new product line has to be updated with the on-going innovations. In fact because any further invention will supersede the previous ones, Cozzi (2003) and Cozzi and Spinesi (2004) assume that in order to absorb the new knowledge created through the vertical innovation process each researcher has to spend costly time and effort. As said above each researcher engaged in the vertical innovation process has to be updated with the on-going innovations in order to introduce a better version of the existing goods, i.e. in order to incorporate all existing techniques of production to minimize costs. We assumed that the updating time cost is inversely proportional to general knowledge, but it is indispensable to innovative activity.

The above considerations imply that technological frontier considered as the accumulated knowledge is related to both quality improving and variety creation – i.e. both vertical and horizontal innovation.

In fact Romer (1990) assumes horizontal innovation and maintains that a researcher working today benefits of all technological advances accumulated over time. The intertemporal spillover within the same sector and between sectors allows researchers to introduce completely new product lines. The author of this thesis agrees with Romer (1990) point of view – also if the assumption of perfectly linear spillovers assumed by the author is questionable – but also think that the horizontal innovation process requires further peculiar factors in order to take place. For this reason, the author of this thesis refers to the original Schumpeterian view of the entrepreneur by considering the entrepreneur not as an individual who applies the problem solving technique accumulated over time, but as a skilled individual endowed of a 'genial capacity' that could not be summarized by a routinized activity as problem solving.

In order to better explain this point it is important to distinguish between two aspects of the innovative activity. Vertical innovation aims to improve an existing product line whereas horizontal innovation creates an entirely new industry. The first kind of innovative process, according to Howitt (1999), entails adapting to a pre-existing product the advances generated by the evolution of general knowledge at the economy wide level. Conversely, horizontal innovation involves a typical entrepreneurial activity in which a new field never existed before is opened thanks both to a pioneer's effort and to the innate ability of the entrepreneur. Hence vertical R&D requires the ability to invent something that her peers typically could not easily invent, that is each researcher engaged in vertical R&D has to go beyond the standard problem solving activity in order to obtain a patent grants. Horizontal R&D requires not only the capacity to invent something that adds new useful, non-obvious, and novel knowledge to the current technological frontier in order to obtain a patent grants, but also requires an "entrepreneurial ability" which allows to discover completely new sectors. Given this peculiar qualitative character of horizontal innovation, it is not unreasonable to assume that people differ in their ability to create market niches, i.e. to escape direct competition with existing incumbents.

To conclude this brief overview of the neo-Schumpeterian approach to economic growth it is worthwhile to underline how the relationship between information appropriability and dissemination has been studied intensively since Schumpeter's (1934, 1939, 1942) seminal works. Despite Schumpeter's contention that market power is the "*most powerful engine of technological progress*" (1942, p.106), two other factors are generally considered better predictors of innovation-intensity. The first is the set of industry-specific variables; the second is the level of technological spillovers and hence the information appropriation and dissemination mechanisms.

1.6 Reconciling Endogenous Growth and the Patent Literature

Robert Merger and Richard Nelson (1990), and Susanne Schotchmer (1991 and 2004) stressed how "*most innovators stand on shoulders of giants*". Innovation is a process sequential and cumulative in nature where each invention builds on previous ideas. Some authors have argued that, particularly in the biosciences and in the software industry, fundamental patents are often overbroad and this can slow down follow-on research. The debate specially warmed up with reference of the ability of basic research to spawn product development for the marketplace. Historical perspective on many technological achievements shows that in most cases the value of an idea cannot be directly embodied into the market value of a good. It is the partial equilibrium patent literature that merits the analyses of the effects of patent law changes on the activity of follow-on researchers. The numerous contributions in this framework showed how the relation between patent scope and innovation incentives is unclear in many cases.

According to the standard Schumpeterian paradigm, R&D is an uncertain activity modelled by a Poisson process. Each (private) R&D firm employs a flow of skilled labor input z in order to obtain, under the assumption of constant return to scale, a flow probability of innovation θz, where θ is the given arrival parameter of the Poisson process. However, as a wide literature on cumulative and sequential innovation (see, for instance, Scotchmer, 1991 and 2004) emphasizes, in most cases the value of an idea cannot be directly embodied into the market value of a good. Think about the practice of research activity in the medical/pharmaceutical sector: once a new chemical active principle for treating a human pathology is individuated, a long period of pure experimental use begins in order to implement the new drug saleable to the drug market.

The contrast between the evidence of an upstream conditioned R&D activity and the conception that only the concrete embodiment of an idea is provided with economic value emerges also from the increasing concern among both scholars and the business community about the ability of researchers to conduct sequential R&D activity effectively (see Heller and Eisemberg, 1998).

After the pioneering microeconomic contributions of Reinganum (1985), Grossman and Shapiro (1987) and Green and Scotchmer (1995), economists became aware of the strategic dimension of sequential research activity. The possibility that in the real world innovators may use the patents they hold just to block future innovators raised a still increasing concern[10]. It has been proposed to adopt a statutory research exemption as a definitive solution to this problem. By research exemption we mean a situation in which,

[10]Moreover, Heller and Eisemberg (1998) suggested the existence of a *tragedy of the anti-commons*, i.e. a proliferation of upstream intellectual property rights which greatly amplify transaction cost of downstream R&D, thus hampering downstream research for biomedical advancement.

in a contest of sequential and cumulative innovations, after have been undertaking research on a research tool and obtained a saleable innovation, the second innovators is allowed, by the judge (or simply by the law if the research exemption is statutory), to infringe the patent held by the first innovator, but the second innovator is not allowed to bring its product to the market[11]. As Susanne Scotchmer argued, "*perhaps counter-intuitively, a research exemption on first innovation works to benefits of its owner*".

The core of the reasoning is in that research activity is intrinsically uncertain. When innovation is cumulative so is its uncertainty: not only in terms of results, but also, and this is what has most relevance here, in terms of the appropriability of such results. Uncertainty in cumulative research environment is central in Hopenhayn, Llobet and Mitchell's (2006) analysis. By extending O'Donoghue, Scotchmer and Thisse's (1998) structure to the case of incomplete information about the quality of the innovations from the patent granting authority, they develop a model of cumulative innovation where new ideas arrive continually. Within the framework of partial equilibrium models, Hopenhayn, Llobet and Mitchell's (2006) work stands out for its completeness, in fact it also provides a very instructive discussion on the different methods available to reward innovators by showing the relative advantages/disadvantages according to the literature (Cornelli and Shankerman, 1999; Scotchmer 1999).

In fact, recent developments of the Schumpeterian growth theory did not miss to acknowledge the importance of accounting for the sequential and cumulative nature of ideas, by identifying basic research with horizontal innovation (Aghion and Howitt, 1996), by merging the patent-design literature and the endogenous growth literature in a general equilibrium framework (O'Donoghue and Zweimuller, 2004), by allowing the possibility for an idea at pre-commercial stages of development, or for an essential part of it, to be stolen and afterward used by agents distinct from the inventor (Cozzi, 2001).

In this framework, O'Donoghue and Zweimuller's (2004) work is particularly interest-

[11]For a primer on the law related aspects of the research exemption and patents see Maurer and Scotchmer (2004) and Mueller (2001 and 2004).

ing in that it identifies a role for patents in providing protection against future innovators: patentability requirement and leading breadth are able to affect the characteristics of new products, or the types of cost reduction that firms pursue, and could compensate the tendencies of sub-optimally small innovations.

I believe that it is important to acknowledge the presence of basic research in all industries, rather than only in the newly created ones. To accomplish this, my work assumes, unlike Aghion and Howitt (1996), that in each sector of the economy the innovation process can be decomposed into two stages: basic research and applied research. In the next Chapter 2, I build a model to analyse the behaviour of the public sector under different intellectual property regimes; I then calibrate the model to the US data and I punctually estimate the basic and applied research productivities after 1980.

Chapter 2

A Macroeconomic Framework for the Analysis of the US Patent Policy

"*The ultimate limits to growth may lie not as much in our ability to generate new ideas, so much as in our ability to process an abundance of potentially new seed ideas into usable forms.*"

(Martin Weitzman, 1998, page 333).

2.1 Introduction

The contribution of this chapter is central to the thesis, as it develops an entirely new macroeconomic framework to address the issue of allowing patents on early-stage research results. The traditional argument in favour of patenting basic research relies on the argument that this will encourage basic research and direct it in a way likely to inspire commercial applications. On the other hand, granting patents means that monopoly power will limit the ultimate exploitation of the commercial potential. Whether protection is worthwhile depends on which effect dominates.

In order to investigate the macroeconomic effects of the trade-off between the incentive provided by property rights to basic research and the resulting monopolistic distortion, this chapter studies the sequential innovation process and evaluates the impact of intellectual property design under different conditions on economic growth. Within a standard Schumpeterian framework, I will try to analytically capture the important distinction between invention and innovation well outlined by the economics of innovation literature. For example, consider the definition provided by Greenhalgh and Rogers (2010):

> *"Another feature (...) of innovation is that the product or process must be introduced into the market place so that consumers or other firms can benefit. This distinguishes an innovation from an invention or discovery. An invention or discovery enhances the stock of knowledge, but it does not instantaneously arrive in the market place as a full-fledged novel product or process. Innovation occurs at the point of bringing to commercial market new products and process arising from applications of both existing and new knowledge."* Greenhalgh and Rogers (2010, page 5).

Evidence of non-applicable discoveries generating over time the necessary foundation for marketable innovations can be found in different sources. For example, Gersbach et al. (2009) provide a detailed report of several cases of scientific discoveries waiting for their marketable potential to be targeted and finally fully exploited.

Hecht (1999) reports as, at the end of 1926, Clarence W. Hansell, researcher at the RCA Rocky Point Laboratory in Long Island, had already outlined the principles of optical fibres bundle functioning; in 1927 RCA was awarded the U.S. patent. However, until 1970, optical fibre had very little practical applicability for commercial use. The second fundamental step to innovation came only with the development of laser technology and the increasing demand for high frequency telecommunication tools in the late 1960's, when a group of researchers at Corning Glass Works began to work on purifying glass. In 1970 they refined an optical fibre bundle using pure SiO2 (it was the purest glass ever made) and awarded the patent for the Optical Waveguide Fibres capable of transmitting 65,000 times more information than metallic wire.

Heller and Eisemberg (1998) have pointed out that the patenting of gene sequences produces a tragedy of the anti-commons, i.e. a crumbling of rights which greatly amplify transaction cost, thus hampering downstream research for biomedical advance. A number of examples of patented research inputs in the process of developing new marketable applications and therapies in biotechnology is collected by the National Research Council's (2004) (2004, pp.74, 75) report.

Several studies in the law and economics of intellectual property documented how, over the last 25 years, U.S. Court decisions switched from the traditional jurisprudential limitation on patentability of early-stage scientific findings lacking in current commercial value to the conception that also fundamental basic scientific discoveries (such as scientific theories, algorithms and genetic engineering procedures) fall in the general applicability of the patent system design. In 1980, in the Diamonds vs. Chakrabarty case, the Supreme Court of United States ruled that microorganism produced by genetic engineering could be patented. The Supreme Court's decision arrived two years before the introduction of the first commercial product, human insulin, obtained with recombinant DNA techniques. Jensen and Thursby (2001) study the licensing practices of 62 US universities. They find that "*Over 75 percent of the inventions licensed were no more than a proof of concept (48 percent with no prototype available) or lab scale prototype (29 percent) at the time of license!*". Moreover, most of the inventions licensed were in such an embryonic state of development, that no one could estimate their commercial potential and the inventor's cooperation was required to get a successful commercial development.

Universities and public laboratories have always been the main performers of basic R&D in the United States and in Europe (OECD, 2004). Certainly, an important reason for the relatively low private contribution to basic R&D is often found in the high degree of uncertainty that this activity involves in terms of future commercial application and success.

2.2 The Model

Consider an economy with a continuum of differentiated final goods sectors with corresponding differentiated R&D sectors, along the line of Grossman and Helpman (1991a) and Aghion and Howitt (1992). Product improvements occur in each consumption good industry, and within each industry, firms are distinguished by the quality of the final good they produce.

Time (indexed by $t \geqslant 0$) is continuous with unbounded horizon and there is a continuum of infinitely-lived dynasties of households with identical intertemporally addictive preferences. Heterogeneous labor, skilled and unskilled, is the only factor of production. Both labor markets are assumed perfectly competitive. In the final good sectors, indexed by $\omega \in [0, 1]$, monopolistically competitive patent holders of the cutting edge quality good produce differentiated consumption goods by combining skilled and unskilled labor, whereas R&D firms employ only skilled labor. At time t, population $P(t)$ is assumed growing at rate $g \geq 0$ and its initial level is normalized to 1.

2.2.1 Households

The representative household's preferences are represented by the following intertemporally additive utility functional[1]:

$$U = \int_0^\infty e^{-rt} u\,(t)\,dt, \tag{2.1}$$

where $r > 0$ is the subjective rate of time preference. Per-family member instantaneous utility $u\,(t)$ is defined as:

$$u\,(t) = \int_0^1 \ln \left[\sum_j \gamma^j d_{jt}\,(\omega) \right] d\omega, \tag{2.2}$$

[1] To save notation, the initial expectation operator is omitted in this formula. As the experienced reader knows, a more general setting of the consumer problem would not change results, as in this framework, due to perfectly diversifiable risks, the consumer's asset evolves deterministically in equilibrium.

where $d_{jt}(\omega)$ is the individual consumption of a good of quality $j = 1, 2, ...$ (that is, a product that underwent j quality jumps) and produced in industry ω at time t. Parameter $\gamma > 1$ measures the size of the quality upgrades. This formulation, the same as Grossman and Helpman (1991) and Segerstrom (1998), assumes that each consumer prefers higher quality products.

The representative consumer is endowed with $L > 0$ units of skilled labor and $M > 0$ units of unskilled labor summing to 1. Since labour bears no disutility it will be inelastically supplied for any level of non-negative wages. Since initial population is normalized to 1, L and M will also equal, in equilibrium, the per-capita supply of skilled, respectively, unskilled labour.

In the first step of the consumer's dynamic maximization problem, they select the set $J_t(\omega)$ of the existing quality levels with the lowest quality-adjusted prices. Then, at each instant, the households allocate their income to maximize the instantaneous utility (2.2) taking product prices as given, in the following static (instantaneous) budget constraint equation:

$$E(t) = \int_0^1 \sum_{j \in J_t(\omega)} p_{jt}(\omega) d_{jt}(\omega)\, d\omega. \tag{2.3}$$

Here $E(t)$ denotes per-capita consumption expenditure and $p_{jt}(\omega)$ is the price of a product of quality j produced in industry ω at time t.

The solution to this maximization problem yields the static demand function:

$$d_{jt}(\omega) = \begin{cases} E(t)/p_{jt}(\omega) \text{ for } j = j_t^*(\omega) \\ 0 \quad \text{otherwise.} \end{cases} \tag{2.4}$$

Only the good with the lowest quality-adjusted price is consumed, since there is no demand for any other good. In fact, as usual in this literature, this model assumes that if two products have the same quality-adjusted price, consumers will buy the higher quality product - although they are formally indifferent between the two products - because the quality leader can always slightly lower the price of its product and drive the rivals out of the market.

Let us define $j_t^*(\omega) \equiv \max\{j : j \in J_t(\omega)\}$. Using the instantaneous optimization results, equation (2.2) can be reformulated as follows:

$$
\begin{aligned}
u\,(t) &= \int_0^1 \ln\left[\gamma^{j_t^*(\omega)} E(t)/p_{j_t^*(\omega)t}(\omega)\right] d\omega = & (2.5)\\
&= \ln[E(t)] + \ln(\gamma)\int_0^1 j_t^*(\omega)d\omega - \int_0^1 \ln[p_{j_t^*(\omega)t}(\omega)]d\omega. & (2.6)
\end{aligned}
$$

Therefore, given the independent and - in equilibrium and by the law of large number - deterministic evolution of the aggregate quality jumps and prices, the consumer will only choose the piecewise continuous expenditure trajectory, $E(\cdot)$, of each family member that maximizes:

$$U = \int_0^\infty e^{-rt}\ln[E(t)]dt. \tag{2.7}$$

Assume that all consumers possess equal shares of all firms at time $t = 0$. Letting $W(0)$ denote the present value of human capital plus the present value of non-human asset holdings at $t = 0$, each individual's intertemporal budget constraint is:

$$\int_0^\infty e^{-I(t)}e^{gt}E(t)dt \leqq W(0) \tag{2.8}$$

where $I(t) = \int_0^t i(s)ds$ represents the equilibrium cumulative real interest rate up to time t.

Finally, the representative household chooses the time pattern of consumption expenditure to maximize (2.7) subject to the intertemporal budget constraint (2.8). The optimal expenditure trajectory satisfies the Euler equation:

$$\dot{E}(t)/E(t) = i(t) - (r + g) \tag{2.9}$$

where $i(t) = I(t)$ is the instantaneous market real interest rate at time t.

Euler equation (2.9) implies that a constant (steady state) per-capita consumption expenditure is optimal when the instantaneous market interest rate equals the consumer's subjective discount rate r plus the population growth rate g. Since preferences are homothetic, in each industry aggregate demand is proportional to the representative consumer's one. E denotes the aggregate consumption spending and d denotes the aggregate demand.

2.2.2 Firms' behaviour in the Final Good Sectors

Constant returns to scale characterizes technology in the (differentiated) manufacturing sectors,

$$y(\omega) = X^{\alpha}(\omega) M^{1-\alpha}(\omega), \text{ for all } \omega \in [0,1], \tag{2.10}$$

where $\alpha \in (0,1)$, $y(\omega)$ is the output flow per unit time, $X(\omega)$ and $M(\omega)$ are, respectively, the skilled and unskilled labour input flows in industry $\omega \in [0,1]$. Letting w_s and w_u denote the skilled and unskilled wage rates, in each industry the quality leader seeks to minimize its total cost flow $C = w_s X(\omega) + w_u M(\omega)$ subject to constraint (2.10). For $y(\omega) = 1$, the solution to this minimization problem yields the conditional unskilled (2.11) and skilled (2.12) labour demands (i.e. the per-unit labour requirements):

$$M(\omega) = \left(\frac{1-\alpha}{\alpha}\right)^{\alpha} \left(\frac{w_s}{w_u}\right)^{\alpha}, \tag{2.11}$$

$$X(\omega) = \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha} \left(\frac{w_u}{w_s}\right)^{1-\alpha}. \tag{2.12}$$

Thus the (minimum) cost function is given by:

$$C(w_s, w_u, y) = c(w_s, w_u)y \tag{2.13}$$

where $c(w_s, w_u)$ is the per-unit cost function:

$$c(w_s, w_u) = \left[\left(\tfrac{1-\alpha}{\alpha}\right)^{-(1-\alpha)} + \left(\tfrac{\alpha}{1-\alpha}\right)^{-\alpha}\right] w_s^{\alpha} w_u^{1-\alpha}. \tag{2.14}$$

Let $P(t)$ denote population size at time t. Since unskilled labour is uniquely employed in the final good sectors and all price variables (including wages) are assumed to instantaneously adjust to their market clearing values, unskilled labour aggregate demand $\int_0^1 M(\omega)\, d\omega$ is equal to its aggregate supply, $MP(t)$, at any date. Since industries are symmetric and their number is normalized to 1, in equilibrium[2] $M(\omega) = MP(t)$.

The choice of unskilled labour as numeraire imposes $w_u = 1$. From equations (2.11) and (2.12) the firm's skilled labour demand are derived as negatively depending on skilled (/unskilled) wage (ratio):

$$X(\omega) = \frac{1}{w_s}\left(\frac{\alpha}{1-\alpha}\right) MP(t). \tag{2.15}$$

In per-capita terms,

$$x(\omega) \equiv \frac{X(\omega)}{P(t)} = \frac{1}{w_s}\left(\frac{\alpha}{1-\alpha}\right) M. \tag{2.16}$$

In each industry, the final sector is characterised as a contestable market. More precisely, one firm produces the top-quality product and a competitive fringe produces the second-best quality product. This is due to the assumption, usual in the quality-ladder endogenous growth literature, that old patents expire as soon as a better quality is introduced.

The top-quality monopolist profit function in per-capita terms is given by:

$$\pi_{jt}(\omega) = p_{jt}(\omega)d_{jt}(\omega) - c(w_s, w_u)d_{jt}(\omega) = \tag{2.17}$$

$$= p_{jt}(\omega)E(t)/p_{jt}(\omega) - c(w_s, w_u)E(t)/p_{jt}(\omega) = \tag{2.18}$$

$$= E(t) - c(w_s, w_u)E(t)/p_{jt}(\omega), \tag{2.19}$$

[2] More generally, with mass $N > 0$ of final good industries, in equilibrium $M(\omega) = \frac{MP(t)}{N}$.

which is monotonically increasing in $p_{jt}(\omega)$. Due to Bertrand (price) competition, the top-quality producer price-limits the competitive fringe. In other words, since demand functions (2.4) imply that within each industry product innovation is non-drastic[3], each quality leader will fix its (limit) price by charging a mark-up γ over its unit cost (remember that parameter γ measures the size of product quality jumps):

$$p = \gamma c(w_s, 1) \Rightarrow d = \frac{E}{\gamma c(w_s, 1)}. \tag{2.20}$$

Note that the mark-up set by the top-quality producer is equal to the quality parameter γ, capturing the constant marginal rate of substitution across qualities for the consumer In fact, the price charged by the top-quality producer cannot exceed its "utility-value" for the consumer, because otherwise she will buy from the competitors, who price at the unit-cost."

Hence each monopolist earns a flow of profit, in per-capita terms, equal to:

$$\begin{aligned} \pi_{jt} &= \frac{\gamma - 1}{\gamma} E = (\gamma - 1) \frac{w_s x}{\alpha} \\ \pi_{jt} &= (\gamma - 1) \frac{1}{1 - \alpha} M. \end{aligned} \tag{2.21}$$

It follows that:

$$\frac{\gamma - 1}{\gamma} E = (\gamma - 1) \frac{1}{1 - \alpha} M \Rightarrow E = \frac{\gamma}{1 - \alpha} M. \tag{2.22}$$

Interestingly, equation (2.19) implies that in equilibrium total expenditure is always constant. Therefore, the Euler equation implies a constant real interest rate:

$$i(t) = r + g. \tag{2.23}$$

[3] Following Aghion and Howitt's (1992) and (1998), an innovation is defined as drastic if generates a sufficiently large quality jump to allow the new monopolist to maximize profits without risking the re-entry of the previous quality producers. Given the unit elastic demand, here the unconstrained profit maximizing price would be infinitely high: that would induce the previous quality to re-enter.

2.2.3 Research Sectors

The Mechanics of the R&D, Scale Effects, and Preliminary Results

In each industry, the R&D activity is a two stage process by which, first a new idea is invented upstream (a seminal idea) and then it is used to find the way to introduce a higher quality product. A seminal idea is a new, non-obvious, non-tradeable finding, necessary to research on the final product innovation: hence upstream ideas are *research tools*.

Of course, assuming a two-stage R&D process can be viewed as an albeit stylized approximation of a more complex research process.

Hence the whole set of industries $\{\omega \in [0,1]\}$ can be sub-divided into two subsets of industries: at each date t, there are industries $\omega \in A_0$ with (temporarily) no research tools and, therefore, with one patent holder on the final product, no applied research, and a mass of basic (upstream) researchers, and the industries $\omega \in A_1 = [0,1]\backslash A_0$, with one seminal idea and one patent holder on the final product, and a mass of applied (downstream) researchers directly challenging the incumbent monopolist. The following Figure 1 illustrates the dynamics of the flows of industries from a condition to the other: when a quality improvement occurs in an $\omega \in A_1$ industry, the innovator becomes the new quality leader and the industry switches from A_1 to A_0. Similarly, when a seminal idea discovery arises in an industry $\omega \in A_0$ this industry switches to A_1.

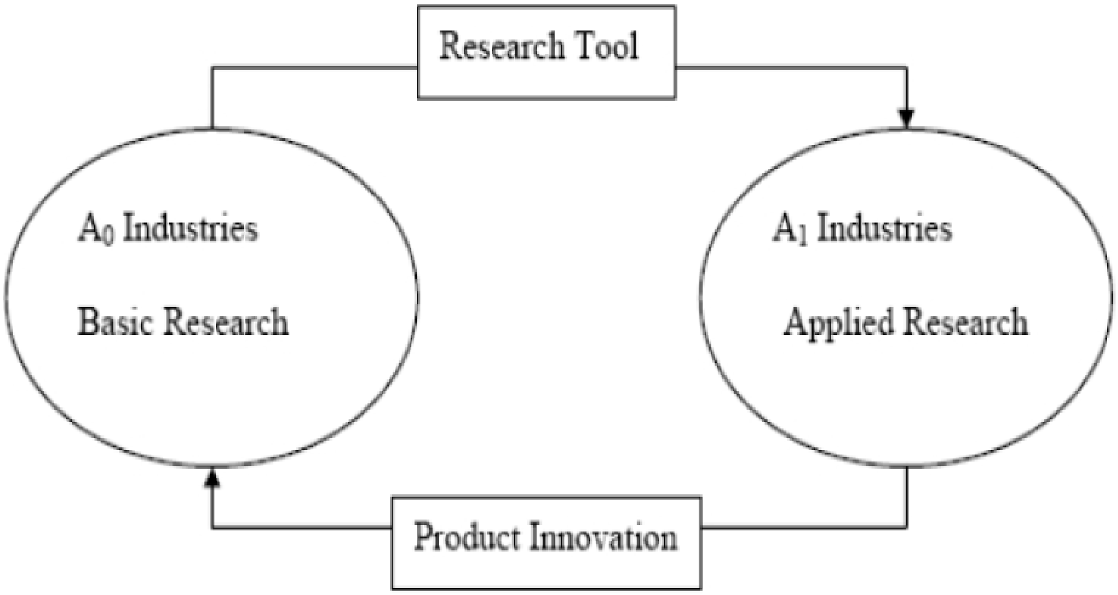

Figure 1: Representation of the economy by flows of Industries

Notice that in this multisector two-stage environment with perpetual innovation basic R&D alternates with applied R&D in all sectors of the economy. The two sets A_0 and A_1 change over time, even if the economy will eventually tend to a steady state. Assume that at any instant it is possible to measure the mass of industries without any seminal idea as $m(A_0) \in [0,1]$, and the mass of industries with an uncompleted seminal idea as $m(A_1) = 1 - m(A_0)$. Clearly, in the steady state these measures will be constant, as the flows in and out will offset each other. The analytical structure showed by figure 1, represents the core of the approach here adopted: analysing the economy innovative performance in terms of flows of industries which are in turn determined by the basic research and applied research outcomes.

Let $i = B, A$ denote basic or applied research. $N_i(\omega, t)$ indicates the mass of basic research skilled labor employment and, respectively, applied research skilled labour in sector $\omega \in [0,1]$ at date t. A researcher's Poisson process arrival rates for a seminal idea, or for a completion (i.e. he product innovation), is $\theta_i\left(N_i(\omega,t), P(t), \omega, t\right)$, decreasing in the aggregate sectoral R&D labor, $N_i \geq 0$. In particular, we specify the Poisson process arrival rates for a basic and applied research labour unit respectively as

$$\theta_B(N_B(\omega,t),P(t),\omega,t) \equiv \frac{\lambda_0}{P(t)}\left(\frac{N_B(\omega,t)}{P(t)}\right)^{-a}, \omega \in A_0 \quad (2.24)$$

$$\theta_A(N_A(\omega,t),P(t),\omega,t) \equiv \frac{\lambda_1}{P(t)}\left(\frac{N_A(\omega,t)}{P(t)}\right)^{-a}, \omega \in A_1 \quad (2.25)$$

where $\lambda_k > 0$, $k = 0, 1$, are R&D productivity parameters and constant $0 < a < 1$ is an intra-sectoral congestion parameter, capturing the risk of R&D duplications, knowledge theft and other diseconomies of fragmentation in the R&D. Each Poisson process - with arrival rates described by (2.24)-(2.25) - governing the assumed two-stage innovative process is supposed to be independent across researchers and across industries. Hence the total amount of probability per unit time of inventing a basic idea in a sector $\omega \in A_0$ at date t is $N_B\theta_B$ and the total amount of probability per unit time of completing a basic idea in a sector $\omega \in A_1$ is $N_A\theta_A$.

Equations (2.24)-(2.25) imply that the probability intensity of the invention of a research tool decreases with population. This assumption, shared by Dinopoulos and Segerstrom (1999), captures the difficulty of improving a good in a way that renders a larger population happier[4]. Notice that, consistently with the assumption that the risk of R&D duplications declines with the difficulty of duplications and that the industrial espionage activities are rendered more complicated with the technological difficulty of the ideas being targeted, here the congestion externality, parameterized by a, is assumed to decrease with population. The specific form postulated for increasing technological difficulty is sufficient to guarantee that the equilibrium long run per-capita growth rates do not increase with population (thereby rendering the framework here developed immune to the embarrassing strong scale effect amply discussed in the previous Chapter 1).

Let us express the model by adopting the per-capita notation: define $n_B(\omega,t) \equiv$

[4]Despite its simplicity, this assumption is equivalent to eliminating the strong scale effect by means of an R&D "dilution effect" over an increasing range of varieties, as proved by Peretto (1998), Young (1998), Dinopoulos and Thompson (1998) and (1999), and Howitt (1999).

$\frac{N_B(\omega,t)}{P(t)}$ and $n_A(\omega,t) \equiv \frac{N_A(\omega,t)}{P(t)}$ - where $P(t)$ denotes total population at time t - as the skilled labor employment in each basic and, respectively, applied R&D sector. Moreover, the existence of symmetric equilibria, allows the author to further simplify notation: $n_B(\omega,t) \equiv n_B(t)$ and $n_A(\omega,t) \equiv n_A(t)$. Notice that there is no loss of generality if in what follows the more microeconomic-oriented reader interprets such derivations under the assumption of constant population, implying that researchers' probability intensities are normalized to $\theta_B \equiv \lambda_0 n_B^{-a}$ and $\theta_A \equiv \lambda_1 n_A^{-a}$.

In every equilibrium, the per-capita mass of skilled labour employed in manufacturing sector $\omega \in [0,1]$ at time t, labelled $x(\omega,t)$, will be constant across sectors and equal to $x(\omega,t) = x(t)$. Hence, after dropping time indexes for simplicity[5], in every equilibrium, the following skilled labor market equilibrium in per-capita terms must hold:

$$L = \frac{1}{w_s}\left(\frac{\alpha}{1-\alpha}\right)M + m(A_0)n_B + m(A_1)n_A. \tag{L}$$

Equation (L) states that, at each date, the aggregate supply of skilled labor, L, finds employment in the manufacturing firms of all $[0,1]$ sectors, x, and in the R&D laboratories of the A_0 sectors, n_B, and of the A_1 sectors, n_A.

The more micro-oriented reader may regard equation (L) as stating that the supply of R&D resources is described by an upward sloping curve - $L - x$ - in unit R&D cost.

2.2.4 Unpatentable Basic Research

A Model for the Public Basic Research Sector

The aim of this section it to describe a pre-1980 US normative environment. The current European patenting regime - still heterogeneous[6], with more restricted patent subject

[5] Of course time dependence is implicit, as employment variables, wage, and the mass of sectors in which a half idea is present, respectively absent, keep changing over time, except in the steady state.

[6] Strong research exemptions being present in some countries, such as Belgium and Germany.

matter[7] - shares many features of this scenario.

Lacking the patent protection of the first seminal ideas, the innovative process would need to resort to non-profit motivated R&D organizations to take place: publicly funded universities and laboratories have often been motivated by the induced scientific spillover on potentially marketable future technical applications.

The public sector is liable to an important form of moral hazard in its role of basic research performer: if researchers get paid regardless of the profitability of their discoveries, their activity is "curiosity driven", and their rewards are not aligned to downstream needs. Hence their efforts might, from a social viewpoint, be wrongly targeted. To stylize the partially "unfocused" research behaviour of the public researchers, assume that the public researchers are totally indifferent to sectorial profitability: when in a sector ω that lacked a seminal idea, i.e. belonged to A_0, a research tool appears, i.e. it becomes A_1, the public R&D workers keep carrying out basic research in that sector. More formally, here we assume that the public researchers are allocated across different industries according to a uniform distribution. This may represent the case of university researchers who keep investigating along intellectual trajectories even when they know that no private firm will ever profit from adapting to their market the new knowledge they may create. Unguided by the invisible hand, researchers will keep devoting their efforts just to prove that they are able to re-invent a second, third, ..., n^{th} genial - but socially useless - idea aimed at enriching their *cv* and justifying their academic carrier (see Aghion and Tirole, 1994 a and b).

The traditional argument, highlighted by Green and Scotchmer (1995), stressed the role of the patent system in providing the upstream inventor with the right incentive while preserving at the same time the incentive to follow-on (applied) product development in contest of two-stage cumulative R&D process.

By assuming basic researchers uniformly distributed across industries, differently from

[7] Unlike the US Patent Code, stressing the "utility" of a protected idea, the European Patent Convention stresses the clearly defined "industrial applicability" of the patented object. This renders the patentability of each research tool more disputable.

other important models in this field, like Bessen and Maskin (2009), this study emphasizes a new role for the patent system: providing the R&D laboratories with the right incentive and to urge them to divert their resources from the temporarily unimportant projects and quickly reallocate them towards more profitable aims. In other words, in a macroeconomic model, the patent system has the ability to target the basic research activity and to direct it towards the most expected profitable applications. This is why, the scenario considered by this section, could be rightly said to depict a model for the public basic research sector.

The government exogenously sets the fraction, $\bar{L}_G \in [0, L]$, of population of skilled workers to be allocated to the heterogeneous research activities conducted by universities and other scientific institutions and funds it by lump sum taxes on consumers. Assuming lump sum taxation guarantees that government R&D expenditure does not imply additional distortions on private decisions.

The ratio of skilled workers, $\bar{L}_G$, is also equal the per sector amount of R&D. Therefore, the seminal ideas arrival rate in basic research is $\theta_O \equiv \lambda_0 \bar{L}_G^{-a}$. Therefore the probability that in any given A_0 sector a useful seminal idea will appear is $\bar{L}_G \theta_B \equiv \bar{L}_G^{1-a} \lambda_0$, whereas the probability that an existing seminal idea generates a new marketable product is $n_A \theta_A = n_A^{1-a} \lambda_1$.

Let v_L^0 denote the value - normalized by population - of a monopolistic firm producing the top quality product in a sector $\omega \in A_0$, and let v_L^1 indicate the value - normalized by population - of a monopolistic firm producing the top quality product in a sector $\omega \in A_1$. These two types of quality leaders - competing instantaneously a la Bertrand - both earn the same profit flow, π, but the first type has a longer expected life, before being replaced by the new quality leader, i.e. by the patent holder of the next version of the kind of product it is currently producing. In sectors that are currently of type A_0 the applied R&D firms cannot enter because there is no research tool to be exploited: they shall wait until the public researcher invent one, causing that sector to switch into A_1. Instead, in an A_1 sector applied R&D firms hire skilled workers in order to complete the freely available research tool. Since there is free entry into applied research, the R&D

firm's expected profits are dissipated[8] and transferred to skilled workers.

The following equations describe the financial arbitrage conditions for the R&D sector:

$$
\begin{aligned}
w_s &= \lambda_1 n_A^{-a} v_L^0 && (2.26a)\\
r v_L^0 &= \pi - \bar{L}_G^{1-a} \lambda_0 \left(v_L^0 - v_L^1\right) + \frac{d v_L^0}{dt} && (2.26b)\\
r v_L^1 &= \pi - n_A^{1-a} \lambda_1 v_L^1 + \frac{d v_L^1}{dt}. && (2.26c)
\end{aligned}
$$

where r denotes the relevant interest rate. Equation (2.23a) is the free entry condition in the applied R&D in any given sector $\omega \in A_1$: it equalizes the skilled wage to the marginal expected gains of completing the next version final product multiplied by the value of its patent, v_L^0. Equation (2.23b) shows that perfectly efficient financial markets lead v_L^0 to the unique value that equalizes the risk free interest income[9] achievable by selling the stock market value of a leader in an A_0 industry, $r v_L^0$, and the flow of profit π net of the expected capital loss from being challenged by a seminal idea on a better product in the case a follower appears, $\bar{L}_G^{1-a} \lambda_0 \left(v_L^0 - v_L^1\right)$, plus gradual appreciation in the case of such event[10] not occurring, $\frac{d v_L^0}{dt}$.

Equation (2.23c) equate the risk free income per unit time deriving from the liquidation of the stock market value of a leader in an A_1 industry, $r v_L^1$, and the relative flow of profit π minus the expected capital loss deriving from the downstream applied researcher firm's endeavour, $n_A^{1-a} \lambda_1 v_L^1$, plus the gradual appreciation if replacement does not occur, $\frac{d v_L^1}{dt}$.

[8]Due to perfectly efficient financial market that completely diversify the portfolios of risk adverse savers.

[9]The reader may view r as the real interest rate, exogenous in a microeconomic framework, or equal to the constant subjective rate of time preference in an alternative macroeconomic framework with linear instantaneous utility function (e.g. Aghion and Howitt 1992, or Howitt 1999). Here the Euler equation and the derivative of the population-adjusted firm value with respect to time bear to the simplified expression of safe rate of returns in terms of $r = i - g$ instead of i.

[10]The reader should keep in mind that in continuous time the probability of this event tends to 1 as $dt \to 0$. This is why this probability does not appear in the equation.

The jump processes occurring at the industry level are independent across industries, but, in the aggregate, the law of large number transforms flow probabilities into deterministic flows. Hence, after aggregating over the set of sectors, the dynamics of the mass of industries is described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\, n_A^{1-a} \lambda_1 - m(A_0) \bar{L}_G^{1-a} \lambda_0. \tag{2.27}$$

From the skilled labor market clearing condition:

$$x + \bar{L}_G + (1 - m(A_0)) n_A = L, \tag{2.28}$$

and the definition of x, we get to the equilibrium mass of per-sector challengers:

$$n_A^* = \frac{L - \frac{1}{w_s} \left(\frac{\alpha}{1-\alpha}\right) M - \bar{L}_G}{(1 - m(A_0))}. \tag{2.29}$$

Hence the dynamics of this economy is completely characterized by the differential equation system (2.23a)-(2.23b) and (2.23c), with cross equation restriction (2.26).

In the steady state $\frac{dv_L^0}{dt} = \frac{dv_L^1}{dt} = \frac{dm(A_0)}{dt} = 0$. In the stationary distribution the flow of industries entering the A_0 group must equal the flow of industries entering the A_1 group.

2.2.5 Patentable Basic Research

This section describes a post-1980 US scenario. Once a basic research result is invented in an A_0 sector, it gets protected by a patent with infinite legal life. The effective life of a patent will be dictated by its idea's obsolescence, which is expected finite in any equilibrium we are studying. This fully privatized basic research scenario does not of course exclude the presence of public universities which patent their discoveries: in so far as it spurs innovation, private patent races determine equilibrium quantities[11] anyway.

[11] This is similar to introducing public R&D into Aghion and Howitt's (1992) model: the equilibrium value of n would not change, provided public research is not higher than the equilibrium amount

Post-1980, thanks to the Bayh-Dole and Stevenson-Wydler acts, the boundaries between public and profit-motivated science are correspondingly fuzzy.

The stock value of all firms is determined by privately arbitraging between risk free consumption loans, firm bonds and equities, viewed as perfect substitutes also due to the ability of financial intermediaries to perfectly diversify portfolios and eliminate risk[12]. As in the previous section, the value of the manufacturing monopolistic firms is related to their profits, their expected capital losses (due to obsolescence) and stock market gains. In particular, let v_L^0, and v_L^1 denote respectively the stock market values of an A_0 industry quality leader and of an A_1 industry quality leader. Let v_A, denote the - population adjusted - present expected value of being a research tool patent holder running a downstream applied R&D firm, operating in an A_1 industry and aiming at becoming a new quality leader. Such a firm - similarly to Grossman and Shapiro's (1986) monopolist - will optimally choose to hire an amount n_A of skilled research labour in order to maximize the difference between its expected gains from completing its own research tool - probability of inventing, $(n_A)^{1-a}\lambda_1$, times the net gain from inventing the final product, $(v_L^0 - v_A)$ - and the implied labour cost $w_s n_A$. From its first order conditions, the optimal applied R&D employment in an A_1 sector is obtained:

$$n_A^* = \left[\frac{(1-a)\lambda_1(v_L^0 - v_A)}{w_s}\right]^{\frac{1}{a}}. \tag{2.30}$$

Unlike the previous section, now only the research tool patent holder can undertake applied R&D in its industry, whereas free entry is relegated to the basic research stage, where researchers vie for inventing the basic idea that will render the winner the only owner of a research tool patent worth v_A. Hence their freely entering and exiting mass will dissipate any excess earning, by equalizing wage to the probability flow $\lambda_0 n_B^{-a}$ times

determined by a fully private R&D scenario.

[12]Hence, despite individuals being risk averse, average returns will be deterministic, the risk premia will be zero, and agents will only compare expected returns. As usual in this class of models, the law of large numbers is invoked, which allows individuals who invest in a continuum of sectors with idiosyncratic risk, thereby transforming probabilities into frequencies.

the value of a patent on a seminal idea[13], v_A.

Costless arbitraging between risk free loans and firms' equities implies that at each instant the following arbitrage equations must hold in equilibrium:

$$w_s = \lambda_0 n_B^{-a} v_A \tag{2.31a}$$

$$rv_A = (n_A^*)^{1-a} \lambda_1 (v_L^0 - v_A) - w_s n_A^* + \frac{dv_A}{dt} \tag{2.31b}$$

$$rv_L^0 = \pi - (n_B)^{1-a} \lambda_0 \left(v_L^0 - v_L^1\right) + \frac{dv_L^0}{dt} \tag{2.31c}$$

$$rv_L^1 = \pi - (n_A^*)^{1-a} \lambda_1 v_L^1 + \frac{dv_L^1}{dt} \tag{2.31d}$$

The first equation, (2.28a), is the free entry condition in the basic research market. The second equation (2.28b) equalizes the risk free income deriving from the liquidation of the expected present value of the research tool patent holder in an A_1 industry, rv_A, and the expected increase in value from becoming a quality leader (i.e. completing the product innovation process), $(n_A^*)^{1-a} \lambda_1 (v_L^0 - v_A)$, minus the relative R&D cost, $w_s n_A^*$, plus the gradual appreciation in the case of R&D success not arriving, $\frac{dv_A}{dt}$.

The third equation - (2.28c) - determines the stock value of a quality leader monopolist in an A_0 sector by equalizing its expected profits and capital appreciations to the risk free interest earning, rv_L^0, in case of anticipated liquidation.

Finally, equation (2.28d) must be satisfied by the stock value of a quality leader monopolist in an A_1 sector by equalizing its expected profits and capital appreciations to the alternative risk free interest earning.

Even in case of licensed research tool, the licensee is required to pay a sunk cost to use the tool, which guarantees that R&D activity is non-discouraged. This avoids imposing any impediments to downstream research other than the monopolistic patentee's expected

[13] Unlike Grossman and Shapiro (1987), the research tool patent holder has no incentive to license, because in the present framework the scale diseconomies are assumed at the industry level but not at the firm level.

profit maximization.

By plugging $w_s = \lambda_0 n_B^{-a} v_A$ into the expression of the skilled labour wage ratio, it is possible to re-express the skilled labor demand in manufacturing as:

$$x = \frac{1}{w_s}\left(\frac{\alpha}{1-\alpha}\right)M = \min\left(\frac{n_B^a}{\lambda_0 v_A}, 1\right)\left(\frac{\alpha}{1-\alpha}\right)M. \tag{2.32}$$

Therefore the skilled labor employment in the manufacturing sector is inversely related to the market value of patented research tools. In fact, anticipating higher valued research tools draw more skilled labor from the manufacturing plants into the basic research laboratories, thereby increasing the manufacturing unskilled/skilled labor ratio and consequently raising skilled labor marginal productivity and the relative wage. Since the patent on a seminal idea derives its value from the expectation of future direct production of a marketable good, v_A is in turn pinned down by v_L^0. Therefore, the equilibrium value of the skilled wage is indirectly related to the stream of profits expected from the future commercialization of the product of the completed idea. Unlike the traditional Schumpeterian innovative process, the skilled wage here does not immediately incorporate the discounted expected value of the next commercially fruitful patent, but it does so only one step ahead: the value of the future monopolist is scaled down to current R&D labor wage by the composition of two innovation probabilities.

Since wages are pinned down by the optimal firm size and by the zero profit conditions in the perfectly competitive basic R&D labor markets, the unique equilibrium per-sector mass of entrant basic R&D firms consistent with skilled labor market clearing $L = x + m(A_0)n_B + (1 - m(A_0))\, n_A^*$ is determined as:

$$n_B = \frac{L - x - (1 - m(A_0))n_A^*}{m(A_0)}. \tag{2.33}$$

Unlike the public researchers, in this completely privatized scenario, basic researchers target their activity only in the A_0 sectors.

To complete the analysis, take a closer look at the inter-industry dynamics depicted by

Figure 1. In the set of basic research industries a given number of perfectly competitive (freely entered) upstream researchers, n_B^*, have a flow probability of becoming applied researchers, while in the set of the applied R&D industries each of the n_A^* per-industry applied researchers has a flow probability to succeed. Hence the industrial dynamics of this economy is described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\, \lambda_1 \left(n_A^*\right)^{1-a} - m(A_0) \left(n_B\right)^{1-a} \lambda_0. \tag{2.34}$$

System (2.28b)-(2.28d) and equation (2.31) - jointly with cross equation restrictions x and n_B - form a system of four first order ordinary differential equations, whose solution describes the dynamics of this economy for any admissible initial value of the unknown functions of time v_L^0, v_L^1,v_A, and $m(A_0)$.

In a steady state, $\frac{dv_L^1}{dt} = \frac{dv_L^0}{dt} = \frac{dv_A}{dt} = \frac{dm(A_0)}{dt} = 0$.

Given the analytical complexity of such system, numerical analysis is necessary to analyse the properties of the balanced growth path equilibrium. In all numerical simulations performed, the steady state exists, it is unique and it is saddle point stable for any set of parameter values[14]. Therefore, given an initial condition for $m(A_0)$, there is (locally) only one initial condition for v_L^0, v_L^1, and v_A such that the generated trajectory tends to the steady state vector: the equilibrium is determinate.

Interestingly, the introduction of R&D subsidies is easily done by replacing w_s with $w_s(1-s)$ - where subsidy rate is $0 \leq s \leq 1$ - in equations (2.28a), (2.28b), and (2.27), but not in equation (2.29).

If upstream findings are patentable downstream research can be blocked if the patent holder neither undertakes research nor licenses the protected research tool. In this Schumpeterian framework the incumbent monopolist in the corresponding final good sector is the natural suspect of such anti-innovative behaviour. In fact, by appropriating the patent on a research tool and stopping R&D it will eliminate expected obsolescence on

[14] The files are available from the author of this thesis upon request.

its product, causing its stock market value to jump up to $\frac{\pi}{r}$. Hence, at least in the steady state, the incumbent monopolist will buy the patent in order to block innovation in that sector if its willingness to pay for the research tool is higher than the outsiders' reservation price, that is if and only if

$v_A < \frac{\pi}{r} - v_L^0$.

Simple algebra show that this holds if and only if:

$$\left(\frac{\lambda_1}{\lambda_0}\right)^{\frac{1}{a}} \left(\frac{v_L^0 - v_A}{v_A}\right)^{\frac{1}{a}} (1-a)^{\frac{1-a}{a}} a < \frac{v_L^0 - v_L^1}{v_A}. \tag{2.35}$$

Since v_L^0, v_L^1, and v_A are endogenous in the model, it is impossible to reach an analytical conclusion. The simulations of the privatized economy show that this is certainly satisfied at realistic values of the parameters, which points to a potentially serious blocking patent concern, which, by coupling static inefficiency with dynamic inefficiency, practically vanishes the beneficial side of the Schumpeterian dilemma. Fortunately the usual practice addresses the well know problem[15] of broad intellectual property rights, as, according to Maurer and Scotchmer (2004a, p.90) courts "*usually approve arrangements that remove blocking patents so that firms can bring technologies to market.*" The typical arrangement is compulsory licensing of the patented innovative tool.

2.3 Observed Regularities

A first numerical result seems to suggest that the privatized economy outgrows the public basic research economy when the applied R&D productivity parameter, λ_1, becomes very low: in such cases the equilibrium innovative performance of the private economy with patentable research tools becomes better than the equilibrium growth performance of the economy with a public R&D sector. In fact, if λ_1 is very small or λ_0 is *ceteris paribus*

[15] This is an old problem in the history of patents. As reported by Scotchmer (2004, p. 14), "*James Watt (d. 1819) used his patents to block high-pressure improvements... Watt's refusal to license competitors froze steam-engine technology for two decades.*"

high, the flow out of A_1 will be relatively scarce, whereas the flow out of A_0 will be intense. Therefore in the steady state $m(A_0)$ will be small, thereby exalting the wasteful nature of the public R&D activity uniformly diluted over $[0,1] - A_0$: in this case the social cost of a public R&D blind to the social needs signalled by the invisible hand would overwhelm the social costs of the restricted entry into the applied R&D sector induced by the patentability of research tools.

2.3.1 Calibration of the Model

Patent data are indicators for the innovative performance of the economic system. Well known data suggest that in the U.S. the ratio of the patents granted each year to US residents to applied R&D expenditure per year (in year 2000 dollars) decreased by about four fifths from 1953 to 1982. This indicates the existence of an increasing difficulty in the applied R&D, because prior to 1980 most patents were applied. A reader may conjecture that a public innovation infrastructure poor of selective economic incentives could have been acceptable in a world in which the industrial applications of basic scientific discoveries were rather straightforward. In the modern industry, in which applications of science are eagerly searched by often highly sophisticated downstream researchers, curing the inefficiencies of basic research may become the top priority for a steadily growing economy. This might have motivated the switch in the US patenting rules in the early Eighties and at the same time may provide an explanation for the growing relative disadvantage of the European, Asian and Latin American systems of innovation, in which the protection of research tools is not guaranteed. In order to test this conjecture to the data, in the next section the calibration analysis is performed.

2.3.2 Calibration Analysis

This section provides the calibration of the model to the U.S. data from 1975 to 1981. Moreover it presents the estimation of the difficulty of basic and applied R&D, summarized inversely in the model by the basic/applied productivity parameters, λ_0 and λ_1, whose evolution cannot be inferred by patent statistics, also because in the Seventies basic R&D outcomes could hardly be patented in the US. Only the skilled and unskilled labour, and the numbers of qualified innovations as R&D output, as represented by patents, are utilized as inputs. All variables are normalized by population.

The calibration procedure consists of the following three steps:

1. estimation of the values of the unobservable parameters, λ_0 and λ_1 during the 1975-1981 U.S. period.

2. Use of the estimated parameter values $\hat{\lambda}_0$ and $\hat{\lambda}_1$, in the system of equations of the balanced growth path equilibrium of the Privatized Basic Research Economy.

3. Use of the previous parameters and of the steady state equilibrium amount of basic research labour, $m(A_0)n_B$, estimated in Step 2, into the Public Basic Research Economy scenario, setting $L_G = m(A_0)n_B$, and simulation of the corresponding Public Basic Research Economy model.

L is the percentage of people who were 25 year old or more and who had completed at least 4 years of college, collected by the U.S. Census (2010a), Current Population Survey, Historical Tables[16].

The intra-industry congestion parameter a is set equal to 0.3, consistently with Jones and Williams' (1998) and (2000) calibrations.

$\bar{L}_G$ is the share of S&E doctorate holders in research universities and other academic institutions[17] over the U.S. total employment from 1975 to 1981;

w_s is the skilled premium estimated by Krusell, Ohanian, Rios-Rull and Violante (2000).

[16] Available at: www.census.gov/population/socdemo/education/tabA-2.xls

[17] National Science Foundation, Division of Science Resources Statistics,Science and Engineering Indicators 2006, Appendix table 5-22, available at www.nsf.gov/statistics/seind06/append/c5/at05-22.pdf.

The g data (according to the model, the measure of the actual U.S. innovation rate before 1980) are the number of patents granted to U.S. residents per million inhabitants[18].

The mark-up γ is set equal to 1.68, consistently with what estimated by Roeger (1995) and Martins et al. (1996).

The relevant real interest rate series, r, follows a path similar to the true real interest rates through the Seventies[19]. Several different data sets are known on the real interest rates in the US in the years 1975-1981, all heterogeneous but all significantly different from the usual constant 5% benchmark level. Some estimated real interest rates were even negative in that period[20].

The following Table 2 reports the parameters utilised and their sources:

Table 2: Calibration Parameters

Parameter	Description	Value	Source
γ	Mark-up	1.68	Roeger (1995) and Martins et al. (1996)
a	R&D congestions	0.3	Jones and Williams (1998) and (2000)
L	Skilled Labour (intensity 1979)	Data	U.S. Census, Current Population Survey
M	Unskilled Labour (intensity 1979)	Data	U.S. Census, Current Population Survey
α	Skilled Share in Manufacturing	0.1	Assumption
λ_0	Basic Research Productivity	Estimation	
λ_1	Applied Research Productivity	Estimation	

Solving for the steady state values of the variables in consistently with the data

[18]Source: WIPO, 100 Years Protection of Intellectual Property Statistics, available on http://www.wipo.int/ipstats/en/statistics/patents/.

[19]To obtain as fine estimates of the productivity parameters as possible, ranges from different available real interest rate series consistent with their observed dynamics were constructed, but - as done by Jones and Williams (1998) and (2000) - shifted up towards the stock market average returns, which was 0.03 in the 1969-1978 decade.

[20]See the estimated real interest rate (of three-month treasury bill) series constructed by Mishkin (2006, p. 88-89), based on Mishkin's (1981) method of using the after tax nominal interest rate minus expected inflation.

return the values for the basic/applied R&D productivity parameters, λ_0 (Figure 2) and λ_1(Figure 3).

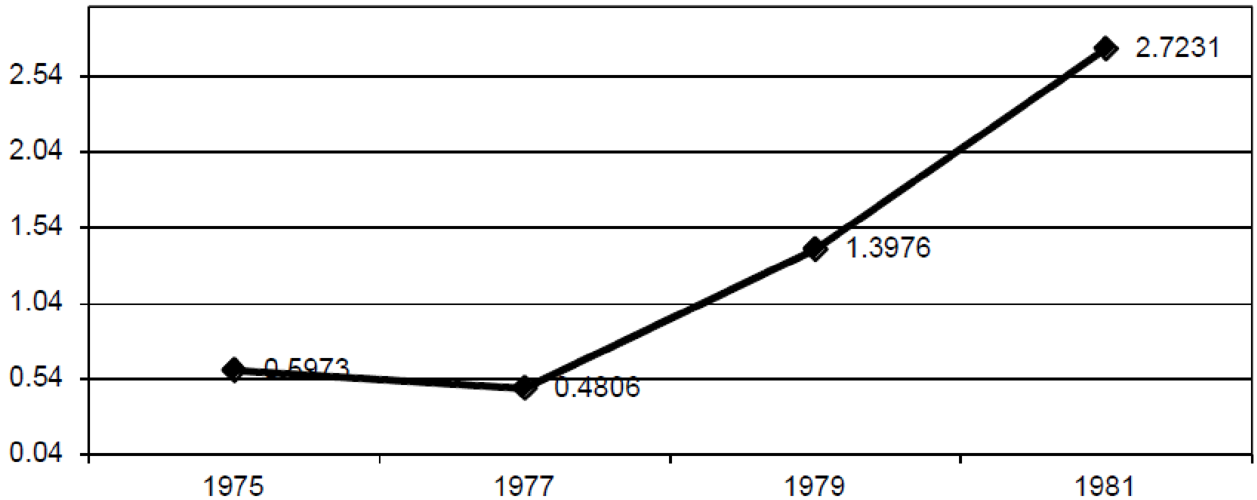

Figure 2: BASIC RESEARCH PRODUCTIVITY
Calibration for the US data from 1975 to 1981

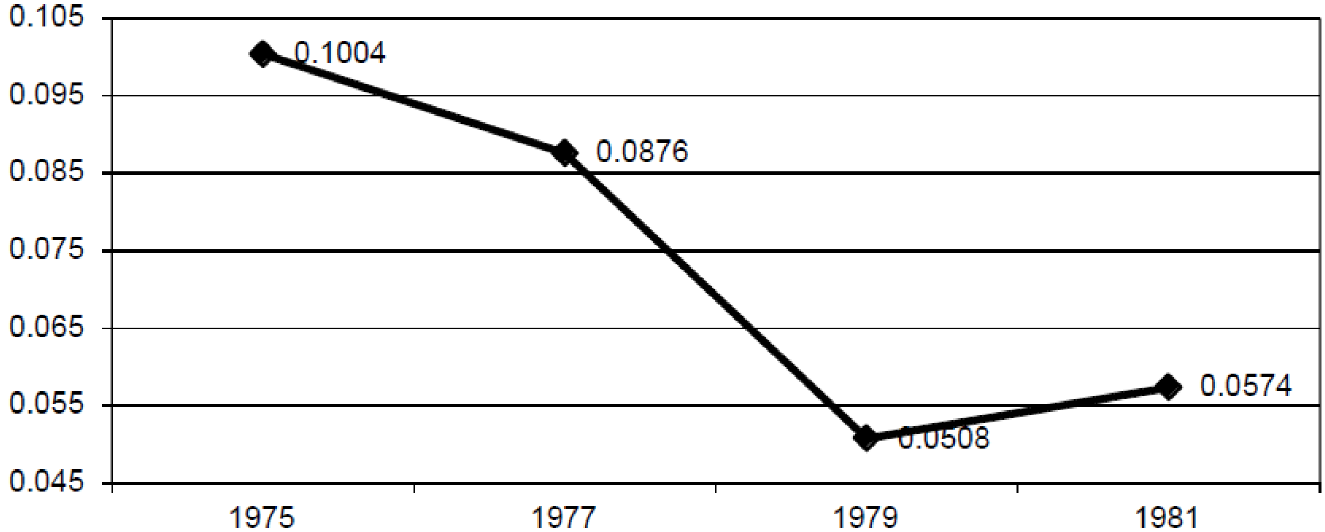

Figure 3: APPLIED RESEARCH PRODUCTIVITY
Calibration for the US data from 1975 to 1981

As the reader can notice, during the Seventies R&D difficulty increased in applied R&D whereas it decreased in basic R&D. Hence, in principle, the relative advantage for the patentability of research tools over the public basic R&D system was getting more and more desirable.

The estimated values of the technological parameters - as well as all the previously described relevant exogenous data - were used to compute the hypothetical steady state equilibrium of the two scenarios - unpatentable research tools versus patentable research tools - for each other year from 1975 to 1981.

Note that this exercise allowed the author of this theses to compare the steady state equilibrium innovative performance of the patentable research tool scenario not only with the actual performance in those years, but also with a hypothetical public scenario constrained to employ the same number of basic researchers as would the privatized system have done. In this way, the possible effects of different levels of employment were eliminated, allowing this study to focus on the induced efficiency gains from research tool patentability.

The following Figure 4 lists the comparative innovation rates in the two scenarios:

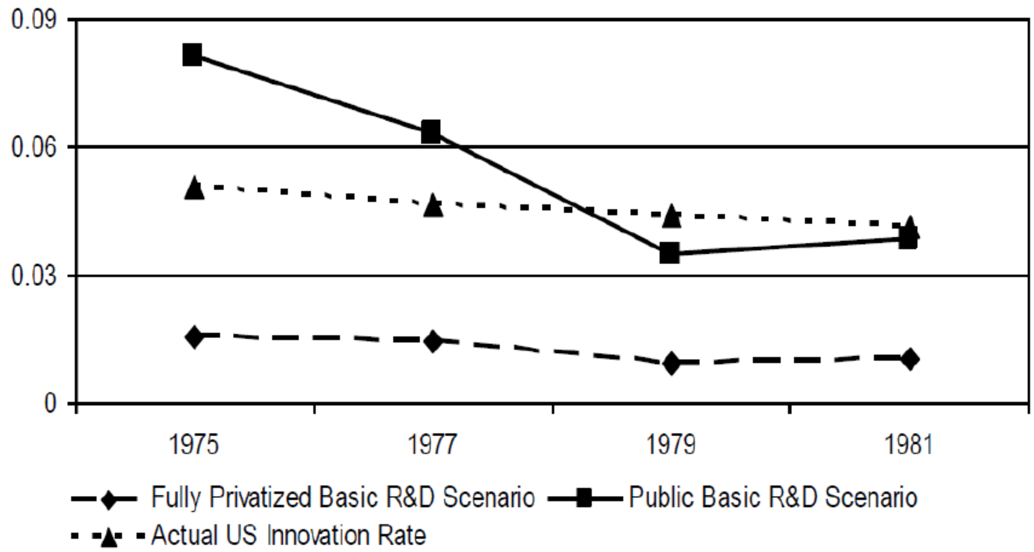

Figure 4: COMPARISON BETWEEN THE INNOVATIVE PERFORMANCES

Calibration on the US data from 1975 to 1981

2.4 Conclusions

From the calibration of the model to the US data, it emerges that at the end of the Eighties the unpatentability of the basic scientific findings imposed less inefficiency to the US innovation system than would the monopolization of research tool have implied. Had the policy makers or the courts been aware of this, maybe they would have postponed the patentability of research tools, which instead prevailed at the beginning of the Eighties. Therefore the analysis carried out in this chapter suggests that the policy change in favour of the research tools patentability occurred in the United States from the early Eighties may not have been the best institutional reaction to the increase in R&D difficulty.

Chapter 3

Alternative Mechanisms to Spur Innovation: Research Exemption and Kremer Patent-Buy-Out

3.1 Introduction

As analysed by the previous Chapter 2, from 1980 on the US national system of innovation has been re-shaped by a sequence of important innovations in the IP law. All these changes pointed to an increase in the appropriability of innovations at their initial stages[1]. The pro-early-innovators environment was also reflected in the increasing protection of trade-secrets - starting in the 80s with the Uniform Trade Secret Act and culminating with the Economic Espionage Act of 1996[2] - as well as in the increasingly positive attitude towards software patents (Hunt, 2001, Hall, 2009), culminating in the Final Computer Related Examination Guidelines issued by the *USPTO* in 1996. The debate on the desirability of basic research patenting over the last 30 years focussed on the possibility for

[1]In particular the Stevenson-Wydler act and the Bayh-Dole act (both passed in 1980) amended the patent law to facilitate the commercialization of inventions obtained thanks to government funding, especially by universities.

[2]See Cozzi (2001) and Cozzi and Spinesi (2006).

the patent law to contemplate a statutory research exemption. Also called "safe harbour exemption[3]", or "217 (e) (1) exemption", or "Hatch-Waxman exemption", the research exemption is actually a common law concept in the US and Canada[4]. In Europe, it is granted statutory dignity by the EU Directives 2001/82/EC (as modified by 2004/28/EC) and 2001/83/EC (as modified by Directives 2002/98/EC, 2003/63/EC, 2004/24/EC and 2004/27/EC), acknowledged by most European countries. It is an exemption to the rights conferred by the patents to the first innovator (i.e. the patent holder), whenever it is possible to recognise that second innovator's research activity entailing the patent infringement was not-for-profit motivated. Under the research exemption doctrine, if the second innovator is successful in developing a saleable product or process, then he or she can patent it and yet infringe another patent (the patented research tool).

In fact, if a patent gives the inventor the exclusive rights to manufacture, use or sell the invention, still it is important to stress that all these rights are *veto*-rights. This chapter develops two alternative scenarios. The first emphasizes the effect of ex-post bargaining between an upstream patent holder and its downstream developer: an innovation can be patented and yet infringe another patent (the patented research tool). This kind of strategic R&D environment is known as "Research Exemption", and it is subject to intense juridical controversies[5], following the famous Supreme Court decision on the Madey *vs.* Duke University case (2002), which practically eliminated the possibility of appealing to it, except under very narrow circumstances. In cases where access to research tools through the marketplace is highly problematic, a research exemption is deemed desirable (Mueller, 2004).

Green and Scotchmer's (1995) model pioneered the microeconomic research on this

[3]The relevance of the research exemption institute is particularly high for the pharmaceutical sector. In fact, there, besides the considerations concerning the sequentiality of the R&D and the use of research tools, the research exemption is advocated by the generic drug manufactures to start the preparation of the compounds during the period antecedent the patent expiring.

[4]In Canada, it is known under the name of "Bolar Provision" or "Roche-Bolar Provision" from the name of the *Roche Products v Bolar Pharmaceutical* case, which first introduced it into the Canadian jurisprudential history.

[5]See Mueller (2004) for a detailed discussion of the research exemption debate in the US.

important issue[6]. In order to cast their insight within the general equilibrium framework developed by Chapter 2 of this thesis, the next section 3.2 assumes that the newly introduced final product is patentable but infringes its research tool. Unlike Green and Scotchmer's (1995) assumption of a unique downstream researcher, here it is assumed that the downstream unauthorized research with a patented research tools can be carried out by a multitude of freely entrant R&D firms, thereby implying a demand effect on R&D inputs dissipating expected profits. The analysis is also valid in the case of reach-through licensing agreements, which seem pervasive in the US.

Michael Kremer (1998) suggested a mechanism to encourage innovation without incurring in the efficiency losses associated with patent generated monopolies. In particular, Kremer (1998) imagined a mechanism in which the government elicits information in order to buy out the patent at a price that reflects the full innovation value. The market value of an invention is likely to be known by the rivals of the firm which has invented it. Hence the government appropriates the patent and auctions it to the rival firms. The winning bid will truthfully reveal the auctioneers' private values because with small probability the government commits to deliver the patent to the highest bidder. With the complementary probability, the government offers the patent back to the inventor at the winning bid price - to make sure the rivals' value is not too low - and, if the inventor does not buy the patent back, the government will transfer to the inventor a mark-up times the winning bid and immediately thereafter it will put the innovation into the public domain. The mark-up is meant to capture the ratio of total surplus to firm's profits. According to Kremer, this reward would better align the inventor's efforts to the approximate social benefits from the innovation.

The following section 3.3 in this chapter develops a scenario in which Kremer's mechanism is used only in the basic research outcomes.

[6] See Scotchmer (2004, section 5.2) for an accessible exposition of this complex issue.

3.2 The Research Exemption Scenario

As in Grossman and Helpman (1991), time is continuous with an unbounded horizon and there is a continuum of infinitely-lived dynasties of expanding households with identical intertemporally additive preferences. Heterogeneous labour, skilled and unskilled, is the only factor of production. Both labour markets are assumed to be perfectly competitive. In the final good sectors $\omega \in [0,1]$ monopolistically competitive patent holders of the cutting-edge-quality good produce differentiated consumption goods by combining skilled and unskilled labour, whereas research firms employ only skilled labour. The analysis of the representative consumer behaviour and the problem of maximization of profit in the final good sector are identical to those modelled in Chapter 2, page 57. The reader is there refered for the most standard analytical details of the model.

Following the framework introduced by the previous Chapter 2, basic and applied research technologies are heterogeneous and the bargaining power of the upstream innovation is subject to institutional changes. Ex post bargaining is rationally expected to transfer to the basic research patent holder a fraction $0 < \beta < 1$ of the value of the final product patent, representing its relative bargaining power.

Let v_B,v_L^0, and v_L^1 denote respectively the present expected value of a basic blocking patent (v_B), an A_0 industry quality leader (v_L^0), and an A_1 industry challenged leader (v_L^1).

Costless arbitrage between risk free activities and firms' equities imply that at each instant the following equations shall hold in equilibrium:

$$
\begin{aligned}
w_s &= \lambda_0 n_B^{-a} v_B && (3.1a)\\
r v_B &= \lambda_1 n_A^{1-a}\left(\beta v_L^0 - v_B\right) + \frac{dv_B}{dt} && (3.1b)\\
w_s &= \lambda_1 n_A^{-a}\left(1-\beta\right) v_L^0 && (3.1c)\\
r v_L^0 &= \pi - n_B^{1-a}\lambda_0\left(v_L^0 - v_L^1\right) + \frac{dv_L^0}{dt} && (3.1d)\\
r v_L^1 &= \pi - n_A^{1-a}\lambda_1 v_L^1 + \frac{dv_L^1}{dt} && (3.1e)
\end{aligned}
$$

Equation (3.1a) is the zero profit condition of a free entrant basic R&D firm in an A_0 industry, equalizing the skilled wage and the probability $\lambda_0 n_O^{-a}$ of inventing a seminal idea times the value v_B of the resulting blocking patent.

Equation (3.1b) states that financial arbitrage pins down the unique value of the blocking patent that equals the risk free income from its sale, rv_B, to the expected present value of maintaining it in an A_1 industry. These are the expected increase in value deriving from someone else's - the n_A downstream researchers' - discovering the industrial application, plus the gradual appreciation in the case of someone else's R&D success not arriving, $\frac{dv_B}{dt}$.

Equation (3.1c) is the free entry condition for downstream completers that rationally expect to appropriate only fraction $1-\beta$ of the value of the final good monopolist. Notice that the expectation of ex-post bargaining or the presence of reach-through licenses introduces a negative incentive effect of downstream innovation, because the infringer's use of a research tool can appropriate only a fraction of the value of its marginal product.

The last two equations have the usual interpretation.

Note that here free entry is assumed into basic and applied research. Each inventor, be she basic or applied, is granted a patent. However, though the first R&D firm that invents a new final product gets the patent anyway, it will infringe the patent held by the previous basic research inventor. Therefore it will have to bargain with the basic research patent holder in order to produce the new version of this good. Such a framework, corresponding to Green and Scotchmer (1995) research exemption regime for pure research tools[7], captures important aspects of the real world disputes between inventors whose patent claims allow the blocking of invention[8].

It is also important to notice that these results do not hinge on assuming that the first stage patent holder undertakes no applied R&D. In fact, the free entry condition (3.1c) dissipates all excess profits from doing so: the research tool patent holder, by hiring a marginal unit of skilled labour to complete its patent would increase its expected gains by $\lambda_1 n_A^{-a} (1-\beta) v_L^0 - w_s = 0$. Hence, it would just be equivalent to one of the free entrants into downstream R&D. Therefore, the model is consistent with an indeterminate R&D participation of the first stage blocking patent holder.

Finally, let the author of this thesis remark how free entry into downstream research vanifies any attempt to resort to ex ante licensing, which would instead hold if, as Scotchmer and Green (1995), Scotchmer (1996), Denicolo' (2001), and Aoki and Nagaoka (2006), we restricted entry to the second stage of R&D to one completing firm.

The industrial dynamics of this economy is described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\,\lambda_1\,(n_A)^{1-a} - m(A_0)\,(n_B)^{1-a}\,\lambda_0. \tag{3.2}$$

This equation, supplemented with the skilled labour market equilibrium condition

$$x + m(A_0)n_B + (1 - m(A_0))\,n_A = L \tag{3.3}$$

and by equation (2.16) for x ($x(\omega) = \frac{1}{w_s}\left(\frac{\alpha}{1-\alpha}\right) M$), determine the equilibrium trajectories.

[7] Also see Scotchmer (2004) and Nagaoka and Aoki (2006) for microeconomic analysis of this important case.

[8] O'Donoghue (1997), O'Donoghue et al. (1998), and O'Donoghue and Zweimueller (2004) are indirectly related, as they capture the role of patent claims in moluding the bargaining between current and future innovators: their concepts of patentability requirement and leading breadth could be re-adapted here to accommodate the blocking power of the upstream patent holder.

The private basic R&D scenario was simulated by using the previously found (in Chapter 2) exogenous parameters λ_0 and λ_1, and compared it with a public upstream research scenario constrained to the same basic research employment as in the privatized case. The implied steady state equilibrium innovation rates are shown in the Figure 5:

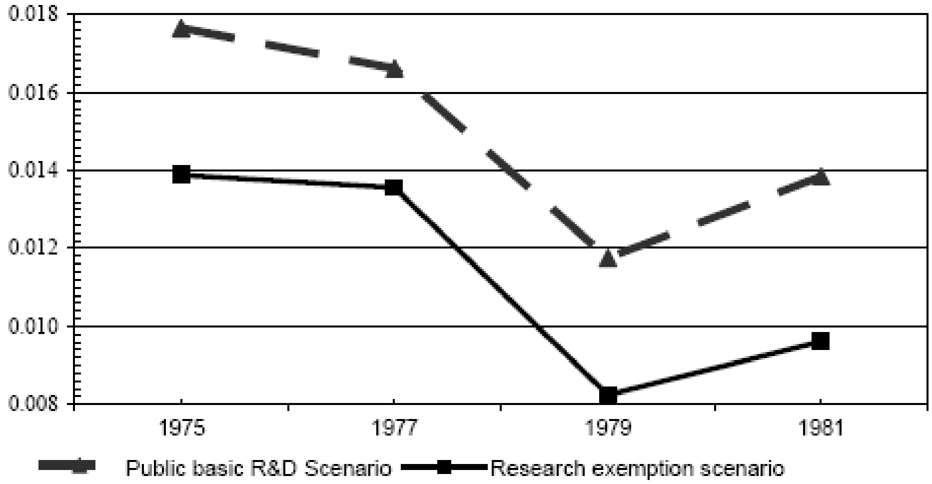

FIGURE 5: COMPARISON OF THE INNOVATIVE PERFORMANCES
Calibration on the US data from 1975 to 1981

As the reader can easily notice, reach-through agreements would the patentability of basic knowledge not be desirable: despite correcting the public research inefficiency, it would have depressed applied R&D too much.

3.3 Kremer's Patent Buy-Out Mechanism

Assume that both basic research and applied research sectors are characterised free entry, because both kinds of discoveries are publicly accessible.Yet, accordin to Kremer's (1998) mechanism, bidders will offer a positive value to the research tool by computing the stock market value of being a research tool patent holder. This "theoretical" value of an applied R&D firm, v_{TA}, is what a successful basic researcher would earn (from the government). Hence the usual free entry condition will dissipate expected R&D profits upstream. Consequently, upstream researchers will target the right sectors, despite downstream research almost never being monopolized. Therefore, the following equations will hold in a Kremer equilibrium:

$$
\begin{aligned}
w_s &= \lambda_0 n_B^{-a} v_{TA} && (3.4a)\\
r v_{TA} &= \lambda_1 \left(n_{TA}^*\right)^{1-a} \left(v_L^0 - v_{TA}\right) - w_s n_{TA}^* + \frac{dv_{TA}}{dt} && (3.4b)\\
w_s &= \lambda_1 n_A^{-a} v_L^0 && (3.4c)\\
r v_L^0 &= \pi - n_B^{1-a} \lambda_0 \left(v_L^0 - v_L^1\right) + \frac{dv_L^0}{dt} && (3.4d)\\
r v_L^1 &= \pi - n_A^{1-a} \lambda_1 v_L^1 + \frac{dv_L^1}{dt} && (3.4e)
\end{aligned}
$$

Equation (3.4a) is the zero profit condition of a free entrant basic R&D firm in an A_0 industry, equalizing the skilled wage to the probability $\lambda_0 n_{TA}^{-a}$ of inventing a research tool times the theoretical value v_{TA} of the resulting applied patent. Interestingly, v_{TA} is endogenously determined in general equilibrium. Hence possible positive innovative effects of Kremer's auctions are dampened, via lower v_{TA}, by higher expected obsolescence and by higher R&D input prices (higher skill premium w_s).

Equation (3.4b) states that financial arbitrage pins down the unique value of the theoretical value v_{TA} of the downstream applied firm that would maximize its profits, by optimally choosing skilled labour employment n_{TA}. The first order conditions yield the optimized value of applied R&D employment:

$$
n_{TA}^* = \left[\frac{(1-a)\lambda_1 (v_L^0 - v_{TA})}{w_s}\right]^{\frac{1}{a}} .
$$

Plugging this expression for n_{TA}^* into (3.4b) determines its stock market value. Expecting this value, the bidding firms willing to monopolize downstream research by appropriating the research tool would bid v_{TA}. This is the value that the government pays to the inventor of this research tool in exchange for appropriating the patent and putting it into the public domain.

Free access to the research tools triggers a patent race in each A_1 industry, thereby pinning down quantities, wage and prices so that the zero expected profit condition (3.4c) holds. Notice the difference between the theoretical applied R&D labour employment, n^*_{TA}, chosen by each would-be monopolistic applied researcher firm and the actual free entry equilibrium value, n_A, of applied R&D labour.

The final two equations determine the values of the monopolistic manufacturing producers in each A_0 and A_1 industry.

As in the previous sections, the industrial dynamics of this economy is described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\,\lambda_1\,(n_A)^{1-a} - m(A_0)\,(n_B)^{1-a}\,\lambda_0. \tag{3.5}$$

The previous equations, supplemented by the skilled labour market equilibrium condition

$$x + m(A_0)n_B + (1 - m(A_0))\,n_A = L,$$

and by equation (2.16) for x, determine the equilibrium trajectories.

The steady state is unique and determinate in all numerical simulations.

After simulating this scenario, the implied innovation rates are plotted in the following Figure 6:

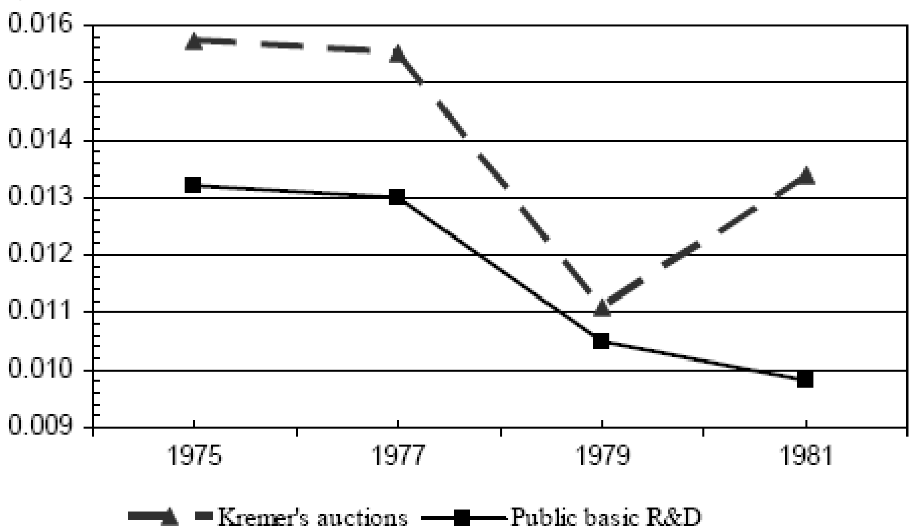

FIGURE 6: COMPARISON OF THE INNOVATIVE PERFORMANCES
Calibration on the US data from 1975 to 1981

As the reader can see, Kremer's (1998) mechanism is the only privatized scenario which dominates the public basic research case. In fact, the R&D efficiency gains from giving upstream researchers the right targets are coupled with the freely accessible patent race to downstream R&D. Our results suggest that if policy makers had known this mechanism a couple of decades before Kremer's result they should have adopted it as a useful complement to the patentability of basic research[9].

3.4 Conclusions

The debate on the effects of the patentability of research tools on the incentives to innovate is still very controversial, not only in the US but also in Europe and in other important areas of the world. This chapter analysed from a general equilibrium perspective the US policy shift towards the extension of patentability to research tools and basic scientific ideas that took place around 1980. These normative innovations have been modifying the industrial and academic lives in the last three decades, raising doubts on their desirability. The losses from the monopolization of basic research induced by intellectual property of research tools have been compared with the inefficacy of public research institutions to promptly react to downstream market opportunities. Results are not a priori unambiguous, which forced the author of this thesis to use the available data to calibrate and simulate the model in order to check if the US did it right in changing their institutions around 1980. According to such calibration, maintaining free access to basic research findings would have been better for innovation despite the inefficiency of the public laboratories and universities. This chapter extended the basic model presented by Chapter 2 to incorporate research exemptions and reach-through licensing, without modifying the main conclusion.

The possibility that in the real world innovators may use the patents they hold just

[9] Adding R&D subsidies in Kremer's scenario would have make it overtake the actual public scenario as well. Of course the "public basic R&D scenario" of Figure 6 costs much less to the taxpayer than the actual public scenario.

to block future innovators, and/or prevent them from commercializing their products, raised a still increasing concern not only among academics. The adoption by the US patent law of a statutory research exemption has been proposed as a definitive solution to this problem. But, by postponing bargaining between innovators it may put the downstream inventor at disadvantage and, as Susanne Scotchmer argued, "*counterintuitively, a research exemption on first innovation works to benefits of its owner*". This chapter has tried to tackle these important issues from a macroeconomic perspective.

Interestingly, it turns out that private research would have been enhanced if the government bought out the research tool patents and rendered them publicly available to the private applied R&D firms, as suggested by Michael Kremer (1998). Notice that in such a framework basic research is indeed patentable, but the government intervention removes the restriction to the downstream patent races. This is consistent with a completely privatized research environment in which the government organizes societal knowledge procurement in a growth enhancing manner. Such third way eliminates public research inefficiency while guaranteeing perfect competition at all stages of research and development. In light of the current international negotiations on the application of TRIPs, our analysis might be helpful in providing insights from the experience of an important turning point in the US national system of innovation.

Chapter 4

Quantitative General Equilibrium Effects of the US Academic Patenting

4.1 Introduction

The key question that modern economies' innovation systems have been facing in the past few decades is: how should basic research be funded in view of maximizing the efficiency of the innovation system as a whole? In other words, is it possible to conceive the privatization of a country's basic knowledge and an efficient system of incentives to basic research? The study presented by this chapter provides a quantitative assessment of the effects of the US patent reforms that, at the beginning of the Eighties, brought to the patentability of research tools, often invented by the university-led research activity.

The birth of the US patent system can be traced back to the very origin of the United States as a nation came into being during the industrial revolution. In fact the US national patent law is founded on Clause 8, Article 1 of the US Constitution, which states that "*The Congress shall have Power (...) to promote the Progress of Science and useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right* *to their respective Writings and Discoveries"*. The first US Patent Act, entitled "An Act to Promote the Progress of Useful Arts" was approved by the Congress in 1790.

Now, it is commonly believed that the time series of the US patents from the second post-war period to the late Nineties displays no significant trend (Segerstrom,1998). It is believed simply because it is true: the growth rate of the number of patents granted to US residents in the period exhibits a pattern oscillating around a null mean, showing the distinctive characteristics of a weakly stationary stochastic process (see the following Figure 7a and 7b).

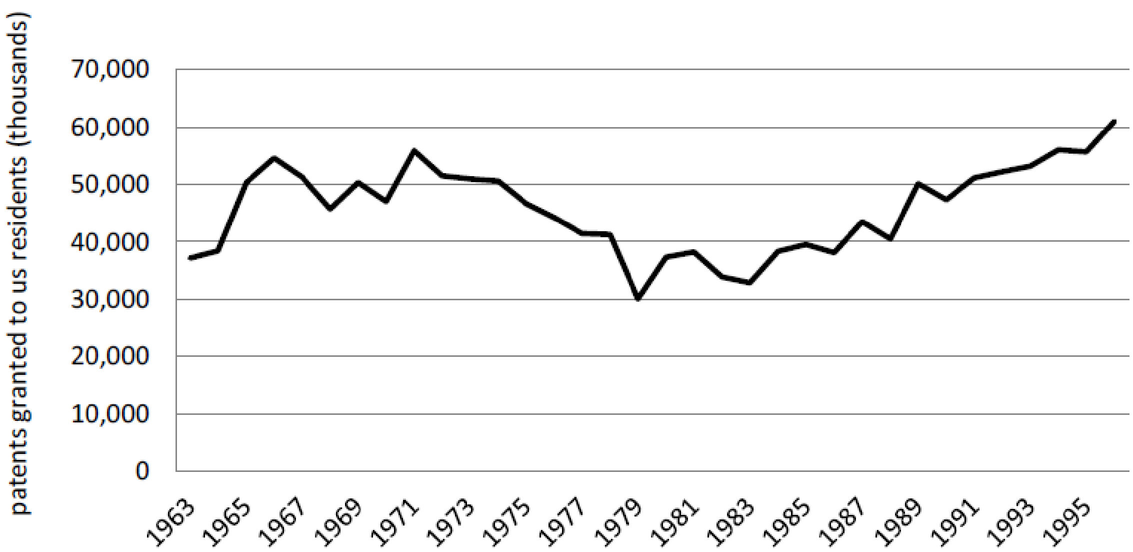

Figure 7a: Patents granted to residents, U.S. 1963-2008.
Source: US Patent and Trademark Office

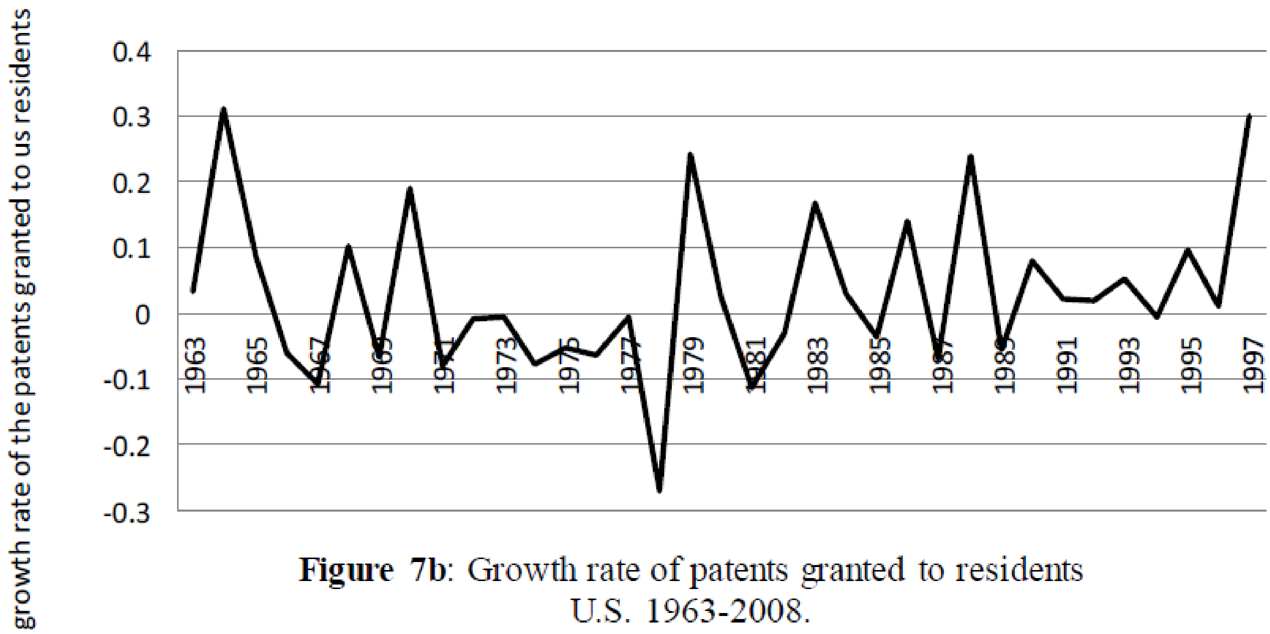

Figure 7b: Growth rate of patents granted to residents
U.S. 1963-2008.
Source: US Patent and Trademark Office

Figures 8a and 8b show the same statistics in the sub-sample 1973-1979. An observer living in 1979 and looking back to the past six years patent data to examine the pattern of the US innovation would probably have a not so positive impression.

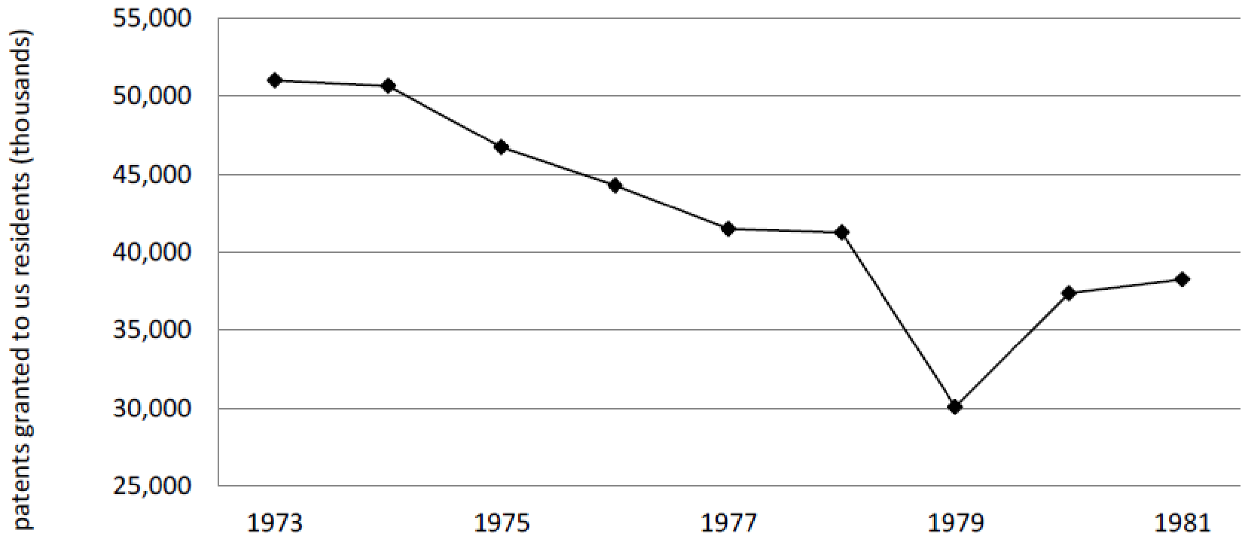

Figure 8a: Patents granted to residents, U.S. 1973-1981
Source: US Patent and Trademark Office

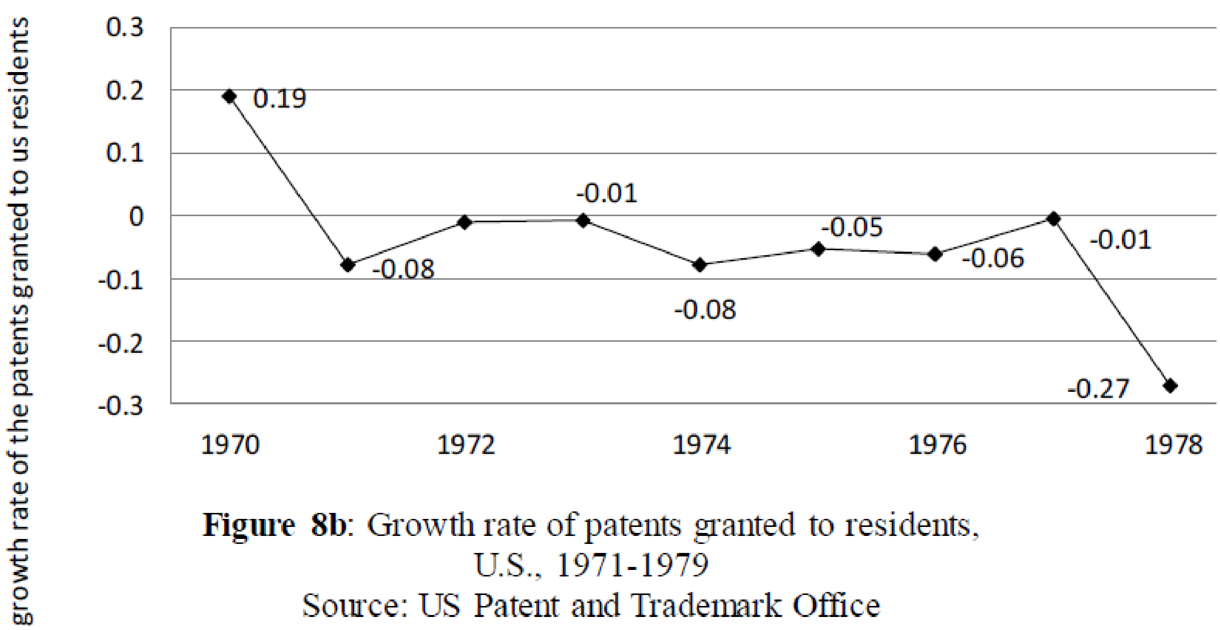

Figure 8b: Growth rate of patents granted to residents, U.S., 1971-1979
Source: US Patent and Trademark Office

This discussion on the data is aimed at depicting the US innovative performance, as it was in a pre-Eighties patent regime. In fact, during the early Eighties in the United States the change occurred in the jurisprudential orientation that led to the patentability of the research tools. The time series on patents will eventually show a significant growth in the number of patented innovations from the end of the Ninethies onward, but it looks reasonable to presume this change is due to the effect of different innovation policies like the 1996's Economic Espionage Act (see Cozzi, 2001 and Cozzi and Pietrosanti, 2005).

The US industrial worldwide challenged leadership and the dissatisfaction about the US innovative performance during that period are very well described by Roberts Hunt's (1999) words:

> *"At the end of the 1990s, it seems ironic to question the performance of the American patent system. (...)*
>
> *Twenty years ago, the perspective was quite different. Reacting to the most severe recession since World War II, and observing the rapid emergence of Japanese and other foreign competitors in the computer and other high technology sectors, policymakers became increasingly concerned about the technological competitiveness of American companies. There was reason for this concern. During the 1970s, private R&D spending and the number of patents issued to U.S. residents stagnated at a time when both were growing rapidly abroad. (...) From the late 1970s to the mid 1980s, the market share of important industries such as steel, automobiles, and semiconductors held by foreign companies increased dramatically.*
>
> *These pressures prompted a re-examination of the American system of intellectual property law, which resulted in many significant legislative changes and important changes in the way federal courts decide patent cases."*[1]

The circumstance that the US innovation policy was influenced by the on-going ob-

[1] Hunt (1999), pp. 15-16.

servation of a downward trend in the number of patents granted to the US is undoubted. Whether or not the responses of such a policy were the most appropriate, needs to be analysed in a macroeconomic theoretical framework incorporating a two-stage R&D investment decision.

At the same time, almost paradoxically, the Seventies saw a generalized flourishing of new inventions developed within the US universities: a sort of a US technological revolution, lacking of a formal US industrial recognition. Gersbach et al. (2009) - reports some of the US university scientific discoveries belonging to that period and the relative impact in terms potential commercial applications (later developed).

The intellectual property reforms aiming at fostering the commercialization of new technologies lead to a dramatic the change in the traditional role played by the academic-led R&D within the US innovation system as universities became more and more involved in industry partnerships and research collaborations.

By highlighting the channels through which the patent policy transmits across the innovation system, this study put forward a possible explanation for the dramatic diminishing in the US patenting activity and, finally, tests this conjecture to the data.

The approach adopted here follows the model presented throughout chapters 2-3. As the reader was able to appreciate, chapters 2 and 3 constitute quite a complete instrument for the innovation policy analysis, providing four different scenarios corresponding to as many different patent system design. Since the aim of this chapter is merely to try to provide the previous chapters with a robust empirical support, this work does not embark a detailed discussion of the theoretical model. However, expositional clarity requires to briefly illustrating the main theoretical aspects.

4.2 A Recall of the Theoretical Model

This work aims at answering the question of the optimal breadth of the patent system. More specifically, we ask if, in the purpose of fostering innovation and growth, would be appropriate to privatize basic research or instead to maintain it into the set of the publicly funded economic activities. Post 1980, the US intellectual property institutions facilitated the patentability of basic research. In this section the model presented throughout chapter 2 is briefly recalled.

The economy is populated by a continuum of infinitely-lived individuals. Time $t \geq 0$ population $P(t)$ is assumed growing at rate $g \geq 0$ and its initial level is normalized to 1. There is an infinity of sectors (industrial lines), normalized to the unit interval. Each sector is characterized by an R&D sector and a manufacturing sector, where the differentiated consumption goods are produced. The economy labour endowment divides into skilled and unskilled. Skilled labour is the only able to perform R&D activities.

Consumer Analysis

The study of the consumers behaviour (and the resulting optimal consumption trajectory) is pretty standard as in the benchmark Schumpeterian growth model. For the sake of shortness, here it is just briefly exposed, hence the reader interested in a detailed analysis of this part of the model is referred to its original source (Grossman and Helpmann (1991a) pages 86-89). Consistently, with the standard quality ladder growth model (Grossman and Helpman, 1991a and Segerstrom, 1998), here it is assumed that consumers derive utility form consumption according to the following utility function:

$$u(t) = \int_0^1 \ln\left[\sum_j \gamma^j d_{jt}(\omega)\right] d\omega, \tag{4.1}$$

where $d_{jt}(\omega)$ is the individual consumption of a good of quality $j = 1, 2, ...$ (that is, a product that underwent j quality jumps) and produced in industry ω at time t. Parameter $\gamma > 1$ measures the size of the quality upgrades.

Each representative consumer is endowed with $L > 0$ units of skilled labor and $M > 0$ units of unskilled labor summing to 1. Hence he also inelastically supply labour in exchange for any positive wage.

At each instant, the households allocate their income to maximize the instantaneous utility (4.1) subject the following static budget constraint :

$$E(t) = \int_0^1 \sum_{j \in J_t(\omega)} p_{jt}(\omega) d_{jt}(\omega)\, d\omega. \tag{4.2}$$

As usual $E(t)$ is the per-capita consumption expenditure and $p_{jt}(\omega)$ denotes the price of a product of quality j produced in industry ω at time t.

The solution to this maximization problem yields the static demand function:

$$d_{jt}(\omega) = \begin{cases} E(t)/p_{jt}(\omega) \text{ for } j = j_t^*(\omega) \\ 0 \quad \text{otherwise.} \end{cases} \tag{4.3}$$

Households face a dynastic intertemporal utility additively separable in the log of the expenditure. Therefore, the consumer will only choose the expenditure trajectory, $E(\cdot)$, of each family member according to his intertemporal preferences (equation 4.4) subject to the individual's intertemporal budget constraint (equation 4.5):

$$U = \int_0^\infty e^{-rt} \ln[E(t)] dt \tag{4.4}$$

$$\text{subject to } \int_0^\infty e^{-I(t)} E(t) dt \leqq W(0), \tag{4.5}$$

where $W(0)$ denotes the present value of human capital plus the present value of asset holdings at $t = 0$, and $I(t) = \int_0^t i(s)ds$ represents the equilibrium cumulative real interest rate up to time t.

The optimal intertemporal expenditure profile satisfies the following Euler equation:

$$\dot{E}(t)/E(t) = i(t) - (r + g) \tag{4.6}$$

where $i(t) = I(t)$ represents the instantaneous market interest rate at time t.

Manufacturing production

This section describes the firms' behavior in the final good sectors. It closely resemble Section 2.2.2 of Chapter 2. The reader already familiar with such model can easily skip it, without hampering the understanding of the following sections.

The technology of the production occurring in the differentiated manufacturing sectors represented by the following CRS production functions:

$$y(\omega) = X^{\alpha}(\omega) M^{1-\alpha}(\omega), \text{ for all } \omega \in [0,1], \tag{4.7}$$

where $\alpha \in (0,1)$, $y(\omega)$ is the output flow per unit time, $X(\omega)$ and $M(\omega)$ are, respectively, the skilled and unskilled labour input flows in industry $\omega \in [0,1]$. w_s and w_u denote the skilled and unskilled wage rates. In each production line the quality leader seeks to minimize its total cost flow $C = w_s X(\omega) + w_u M(\omega)$ subject to constraint (4.7). Setting $y(\omega) = 1$, the solution to this cost minimization problem are the conditional unskilled (4.8) and skilled (4.9) labour demands (i.e. the per-unit labour requirements):

$$M(\omega) = \left(\frac{1-\alpha}{\alpha}\right)^{\alpha} \left(\frac{w_s}{w_u}\right)^{\alpha}, \tag{4.8}$$

$$X(\omega) = \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha} \left(\frac{w_u}{w_s}\right)^{1-\alpha}, \tag{4.9}$$

and the (minimum) cost function is:

$$C(w_s, w_u, y) = c(w_s, w_u) y \tag{4.10}$$

where $c(w_s, w_u) = \left[\left(\frac{1-\alpha}{\alpha}\right)^{-(1-\alpha)} + \left(\frac{\alpha}{1-\alpha}\right)^{-\alpha}\right] w_s^{\alpha} w_u^{1-\alpha}$ is the per-unit cost function.

Choosing unskilled labour as numeraire imposes $w_u = 1$, hence from equations (4.8) and (4.9) the firm's skilled labour demand are negatively depending on skilled (/unskilled) wage (ratio)[2]:

[2] Since unskilled labour is uniquely employed in the final good sectors and all price variables (including

$$x(\omega) \equiv \frac{X(\omega)}{P(t)} = \frac{1}{w_s}\left(\frac{\alpha}{1-\alpha}\right)M. \tag{4.11}$$

In each industry, at each instant, firms compete in prices. Given demand function (4.3), within each industry product innovation is non-drastic, hence the quality leader will fix its (limit) price by charging a mark-up γ over the unit cost (remember that parameter γ measures the size of product quality jumps):

$$p = \gamma c(w_s, 1) \Rightarrow d = \frac{E}{\gamma c(w_s, 1)}. \tag{4.12}$$

Hence each monopolist earns a flow of profit, in per-capita terms, equal to

$$\pi_{jt} = \frac{\gamma - 1}{\gamma}E = (\gamma - 1)\frac{w_s x}{\alpha} \tag{4.13}$$

$$\pi_{jt} = (\gamma - 1)\frac{1}{1-\alpha}M. \tag{4.14}$$

Equations (4.13) and (4.14) were derived in Chapter 2, but they are reproduced in Chapter 4 for ease of reference. From equation (4.14) follows:

$$\frac{\gamma - 1}{\gamma}E = (\gamma - 1)\frac{1}{1-\alpha}M \Rightarrow E = \frac{\gamma}{1-\alpha}M. \tag{4.15}$$

Therefore, the Euler equation (4.6) implies a constant real interest rate:

$$i(t) = r + g. \tag{4.16}$$

---

wages) are assumed to instantaneously adjust to their market clearing values, unskilled labour aggregate demand $\int_0^1 M(\omega)\, d\omega$ is equal to its aggregate supply, $MP(t)$, at any date. Since industries are symmetric and their number is normalized to 1, in equilibrium $M(\omega) = MP(t)$.

Innovation Process according to the Benchmark Scenario

Chapter 2 and Chapter 3 described four alternative patent policy scenarios. According to the benchmark scenario, basic research is funded exclusively by the government. Applied research, instead, is carried out but private researchers who try to complete the results generated in the first step by transforming them into tradeable products. Then, these products are protected by everlasting patents.

The following Figure 9 reproduces Figure 1 of Chapter 2, and provides a graphical representation of the macroeconomic structure: the whole set of industries $\{\omega \in [0,1]\}$ is divided into two subsets of sectors: at each date t, there are industries $\omega \in A_0$ temporarily lacking basic ideas and, therefore, with one quality leader, no applied research and a mass of basic researchers, and the industries $\omega \in A_1 = [0,1] \setminus A_0$, with one research tool and one quality leader and a mass of applied researchers directly challenging the incumbent monopolist.

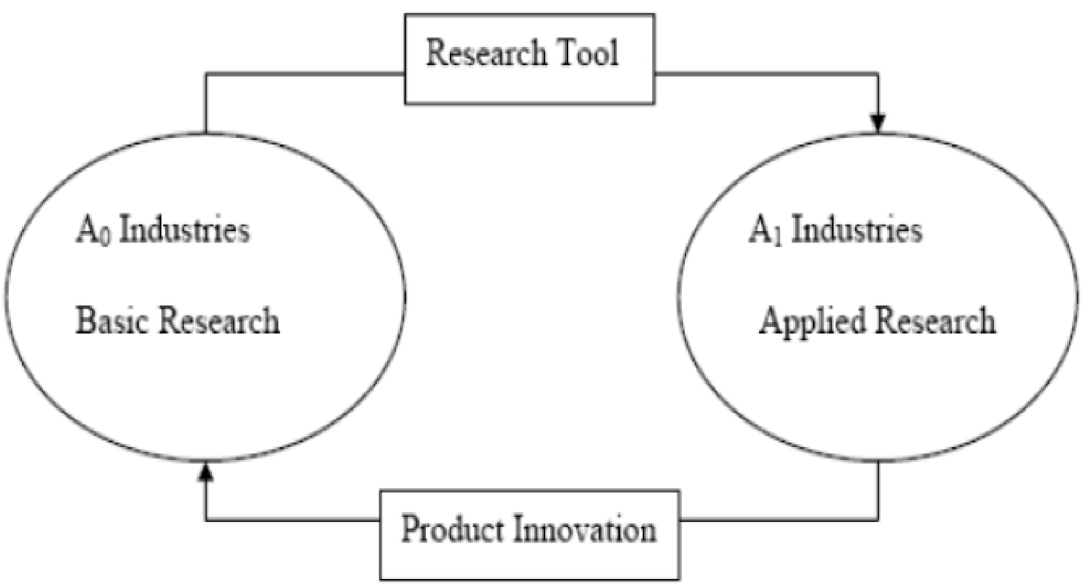

Figure 9: Representation of the economy by flows of Industries

Basic R&D is usefully performed only in $\omega \in A_0$ sectors, whereas applied R&D activity aiming at a direct product innovation is carried out only in A_1 industries. When a quality improvement occurs in an A_1 industry, the innovator becomes the new quality leader and the industry switches from A_1 to A_0. Similarly, when a seminal idea arises in an industry $\omega \in A_0$ this industry switches to A_1.

In the present contest, the expression "innovation system" is adopted to denote the set of individuals and institutions that make an innovation happen. This definition appears important here. In fact, differently from the standard Schumpeterian growth model, institutions and individuals (i.e. firms or self-employed researchers) do not usually share a common motivation for their activity. More precisely, according to the Schumpeterian literature the aim of the R&D firms is to secure the profit associated with the monopolistic rents connected to top-quality manufacturing production. Instead, academic researchers' activity is often "curiosity driven": university researchers keep investigating along intellectual trajectories even when they know that no private firm will ever profit from adapting to their market the new knowledge they may create. Unguided by the invisible hand, researchers keep devoting their efforts just to prove that they are able to re-invent a second, third, ..., n^{th} genial - but socially useless - idea aimed at enriching their *cv* and justifying their academic carrier. Hence their rewards are not aligned to downstream needs and, more important, their efforts might, from a social viewpoint, be wrongly targeted.

To incorporate the partially "un-focussed" research behaviour of the public researchers into a general equilibrium innovation-driven growth model, Chapter 2 assumed that public researchers are allocated across different industries according to a uniform distribution. Given our technological assumptions, this labour is redundant from the economic view point.

Hence, the fixed amount of skilled workers, $\bar{L}_G$, hired in the basic public R&D being uniformly spread over the product space is also equal the per sector amount of R&D. Therefore, each basic research labour unit has a probability per unit of time of making a discovery equal to $\lambda_0 \bar{L}_G^{-a}$. Therefore the probability that in any given A_0 sector a useful research tool will appear is $\bar{L}_G \theta_B \equiv \bar{L}_G^{1-a} \lambda_0$, whereas the probability that an existing research tool generates a new marketable product is $n_A^{1-a} \lambda_1$.

The equilibrium financial arbitrage equations impose the following system to be satisfied:

$$
\begin{aligned}
w_s &= \lambda_1 n_A^{-a} v_L^0 && \text{(4.17a)} \\
r v_L^0 &= \pi - \bar{L}_G^{1-a} \lambda_0 \left(v_L^0 - v_L^1 \right) + \frac{d v_L^0}{dt} && \text{(4.17b)} \\
r v_L^1 &= \pi - n_A^{1-a} \lambda_1 v_L^1 + \frac{d v_L^1}{dt}. && \text{(4.17c)}
\end{aligned}
$$

Equation (4.17a) is the free entry condition in applied research in any given sector $\omega \in A_1$: it equalises the skilled wage to the marginal expected gains of inventing the next version final product.

Equation (4.17b) equalises the risk free interest income[3] achievable by selling the stock market value of a leader in an A_0 industry, $r v_L^0$, to the flow of profit π minus the expected capital loss from being challenged by a research tool discovering, $\bar{L}_G^{1-a} \lambda_0 \left(v_L^0 - v_L^1 \right)$, plus gradual appreciation in the case of such event[4] not occurring, $\frac{d v_L^0}{dt}$.

Equation (4.17c) equals the risk free income per unit time deriving from the liquidation of the stock market value of a leader in an A_1 industry, $r v_L^1$, and the relative flow of profit π minus the expected capital loss deriving from the downstream applied researcher firm's endeavour, $n_A^{1-a} \lambda_1 v_L^1$, plus the gradual appreciation if replacement does not occur, $\frac{d v_L^1}{dt}$.

[3] The reader may view r as the real interest rate, exogenous in a microeconomic framework, or equal to the constant subjective rate of time preference in an alternative macroeconomic framework with linear instantaneous utility function (e.g. Aghion and Howitt 1992, or Howitt 1999). The reader can easily verify that we have used the Euler equation and the derivative of the population-adjusted firm value with respect to time in order to get to the simplified expression of safe rate of returns in terms of $r = i - g$ instead of r.

[4] In continuous time the probability of this event tends to 1 as $dt \to 0$. This is why this probability does not appear in the equation.

After aggregating over the set of sectors, the dynamics of the mass of industries depicted in Figure 9 can be mathematically described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\, n_A^{1-a} \lambda_1 - m(A_0) \bar{L}_G^{1-a} \lambda_0. \tag{4.18}$$

In the stationary distribution the flow of industries entering the A_0 group must equal the flow of industries entering the A_1 group.

The skilled labor market clearing condition applies:

$$x + \bar{L}_G + (1 - m(A_0)) n_A = L, \tag{4.19}$$

from which, together with the definition of x, it is possible to solve for the equilibrium mass of per-sector applied research challengers:

$$n_A^* = \frac{L - \frac{1}{w_s} \left(\frac{\alpha}{1-\alpha}\right) M - \bar{L}_G}{(1 - m(A_0))}. \tag{4.20}$$

Hence the dynamics of this economy is completely characterized by the differential equation system (4.17a)-(4.17c) and (4.17), with cross equation restriction (4.20).

In the steady state $\frac{dv_L^0}{dt} = \frac{dv_L^1}{dt} = \frac{dm(A_0)}{dt} = 0$.

Patentable Research Tools Scenario

As in the previous benchmark scenario, the stock value of all firms is determined by privately arbitraging between risk free consumption loans, firm bonds and equities, viewed as perfect substitutes also due to the ability of financial intermediaries to perfectly diversify portfolios and eliminate risk[5]. As in the previous section, the value of the manufac-

[5]Hence, despite individuals being risk averse, average returns will be deterministic, the risk premia will be zero, and agents will only compare expected returns. As usual in this class of models, we invoke the law of large numbers, which allows individuals who invest in a continuum of sectors with idiosyncratic risk, thereby transforming probabilities into frequencies.

turing monopolistic firms is related to their profits, their expected capital losses (due to obsolescence) and stock market gains.

The optimal applied R&D employment in an A_1 sector is easily obtained from the first order conditions of the applied R&D firm:

$$n_A^* = \left[\frac{(1-a)\lambda_1(v_L^0 - v_A)}{w_s}\right]^{\frac{1}{a}}. \tag{4.21}$$

Costless arbitraging between risk free loans and firms' equities implies that at each instant the following arbitrage equations must hold in equilibrium[6]:

$$w_s = \lambda_0 n_B^{-a} v_A \tag{4.22a}$$

$$rv_A = (n_A^*)^{1-a}\lambda_1(v_L^0 - v_A) - w_s n_A^* + \frac{dv_A}{dt} \tag{4.22b}$$

$$rv_L^0 = \pi - (n_B)^{1-a}\lambda_0\left(v_L^0 - v_L^1\right) + \frac{dv_L^0}{dt} \tag{4.22c}$$

$$rv_L^1 = \pi - (n_A^*)^{1-a}\lambda_1 v_L^1 + \frac{dv_L^1}{dt}. \tag{4.22d}$$

The skilled labor employment in the manufacturing sector is inversely related to the market value of patented research tools:

$$x = \frac{1}{w_s}\left(\frac{\alpha}{1-\alpha}\right)M = \min\left(\frac{n_B^a}{\lambda_0 v_A}, 1\right)\left(\frac{\alpha}{1-\alpha}\right)M. \tag{4.23}$$

The skilled labor market clearing condition states:

$$x + m(A_0)n_B + (1 - m(A_0))\, n_A^* = L \tag{4.24}$$

The unique equilibrium per-sector mass of entrant basic R&D firms consistent with the condition (4.24) is obtained by solving equation (4.24) for n_B:

[6] Please go back to chapter 2, page 71 for a complete description of the meaning of equations (4.21a)-(4.21d).

$$n_B = \frac{L - x - (1 - m(A_0))n_A^*}{m(A_0)}. \tag{4.25}$$

Reconsider the inter-industry dynamics depicted by Figure 9 (which reproduces Figure 1 of chapter 2). In the set of basic research industries a given number of perfectly competitive (freely entered) upstream researchers, n_B^*, have a flow probability of becoming applied researchers, while in the set of the applied R&D industries each of the n_A^* per-industry applied researchers has a flow probability to succeed. Hence the industrial dynamics of this economy is described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\,\lambda_1\,(n_A^*)^{1-a} - m(A_0)\,(n_B)^{1-a}\,\lambda_0. \tag{4.26}$$

System (4.22b)-(4.22d) and equation (4.26) - jointly with cross equation restrictions (4.23) and (4.25) - form a system of four first order ordinary differential equations, whose solution describes the dynamics of this economy for any admissible initial value of the unknown functions of time v_L^0, v_L^1,v_A, and $m(A_0)$.

In a steady state, $\frac{dv_L^1}{dt} = \frac{dv_L^0}{dt} = \frac{dv_A}{dt} = \frac{dm(A_0)}{dt} = 0$.

Experimental Use Defense Scenario

Along the way indicated by Green and Scotchmer's (1995) pioneering microeconomic model on the division of profits between sequential innovators, the recent patent literature results stressed the *veto*-nature of patent rights. As Vincenzo Denicolò (2007) did not miss to remark:

> *"To be of any economic value, patent rights must be enforced: as has aptly been said, a patent is just a "ticket to sue"".*

Put into different words, a patent gives the inventor the exclusive rights to manufacture, use or sell the invention. Hence it is important to characterise all these rights as *veto*-rights. This is the purpose of our fourth scenario: to emphasize the effect of ex-post bargaining between a basic patent holder and its developer. In fact, a product innovation can be patented and yet infringe another patent (the patented research tool). This kind of strategic R&D dimension of the patenting activity is known as "Experimental Use Defence", "Research Exemption Environment" or "Safe Harbour Exemption", and it has been subject to intense recent juridical controversies[7]. In particular, the famous Supreme Court decision on *Madey vs. Duke University* suit[8] *de facto* removed any possibility to appeal for its applicability. As a result after 1980, except under very narrow circumstances, it has not been possible for a patent infringer to be allowed to infringe in the name of science However, in cases where access to research tools through the marketplace is highly problematic, a research exemption is deemed desirable (Mueller, 2004). For this reason, more recently, the Supreme Court of the United Stated overruled such restrictive applicability in the 2006 decision on the *Merck KGaA vs. Integra LifeSciences Ltd.* In this case, the US Supreme Court clarified that broad immunity from patent infringement exists for any pre-clinical research and experimentation that is "reasonably related" to the process of developing new drug candidates.

Ex post bargaining is rationally expected to transfer to the basic research patent holder a fraction $0 < \beta < 1$ of the value of the final product patent, representing its relative bargaining power. Unlike Green and Scotchmer's (1995) assumption of a unique downstream researcher, we here assume that the downstream unauthorized research with a patented research tools can be carried out by a multitude of freely entrant R&D firms, thereby implying a demand effect on R&D inputs dissipating expected profits. Our analysis is also valid in the case of reach-through licensing agreements, which seem pervasive in the US. "*For research tools ... [r]oyalities would be pass-through royalties from the product developed to the tool.*" Maurer and Scotchmer (2004b, page 236).

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[7]See Mueller (2004) for a detailed discussion of the research exemption debate in the US.

[8]The Madey v. Duke University case animated the debate among the academic community. In particular, the cause of the scandal was the court's consideration of Duke's experimental use of Madey's patented invention as part of the university "legitimate business", hence, regardless of the profit motivation the application of a science-motivated research exemption had to be precluded.

We first analyse non-exclusive licenses, while the next subsection will study exclusive pass-through licensing agreements. In all our cases, we assume that the ultimate patent on the final product improvement can be granted to only one firm: the first to invent it.

Let v_B, v_L^0, and v_L^1 denote respectively the present expected value of a basic blocking patent (v_B), an A_0 industry quality leader (v_L^0), and an A_1 industry challenged leader (v_L^1).

Costless arbitrage between risk free activities and firms' equities imply that at each instant the following equations shall hold in equilibrium[9]:

$$w_s = \lambda_0 n_B^{-a} v_B \tag{4.27a}$$

$$r v_B = \lambda_1 n_A^{1-a} \left(\beta v_L^0 - v_B\right) + \frac{dv_B}{dt} \tag{4.27b}$$

$$w_s = \lambda_1 n_A^{-a} (1-\beta) v_L^0 \tag{4.27c}$$

$$r v_L^0 = \pi - n_B^{1-a} \lambda_0 \left(v_L^0 - v_L^1\right) + \frac{dv_L^0}{dt} \tag{4.27d}$$

$$r v_L^1 = \pi - n_A^{1-a} \lambda_1 v_L^1 + \frac{dv_L^1}{dt}. \tag{4.27e}$$

Similarly the previous scenarios, the industrial dynamics of this economy is described by the following first order ordinary differential equation:

$$\frac{dm(A_0)}{dt} = (1 - m(A_0))\, \lambda_1 \left(n_A\right)^{1-a} - m(A_0) \left(n_B\right)^{1-a} \lambda_0. \tag{4.28}$$

The previous equations, supplemented with the skilled labour market equilibrium condition

$$x + m(A_0) n_B + (1 - m(A_0))\, n_A = L, \tag{4.29}$$

and by equation (4.23) for x, determine the equilibrium trajectories.

[9] Please go back to chapter 3, page 88 for a complete description of the meaning of equations (4.21a)-(4.21d).

4.3 Estimating the unobservable

In this section, I ran simulations of the different scenarios. The regularities found suggest that an economy in which public basic research is conducted in a non-profit oriented manner can induce less or more innovations than an economy in which basic R&D is privately carried out. The privatized economy outgrows the public basic research economy when the applied R&D productivity parameter, λ_1, becomes very low: in such cases the equilibrium innovative performance of the private economy with patentable research tools becomes better than the equilibrium growth performance of the economy with a public R&D sector. In fact, if λ_1 is very small or λ_0 is high, the flow out of A_1 will be scarce, whereas the flow out of A_0 will be intense. Therefore in the steady state $m(A_0)$ will be small, thereby exalting the wasteful nature of the public R&D activity uniformly diluted over $[0,1] - A_0$: in this case the social cost of a public R&D blind to the social needs signalled by the invisible hand would overwhelm the social costs of the restricted entry into the applied R&D sector induced by the patentability of research tools.

Patent data are indicators for the innovative performance of the economic system. The aim of this section is to calibrate the different scenarios with U.S. data from 1975 to 1981. The basic/applied productivity parameters, λ_0 and λ_1, whose evolution cannot be inferred by patent statistics because in the Seventies basic R&D outcomes could hardly be patented, are here punctually estimated by using only skilled and unskilled labour as inputs and numbers of qualified innovations as R&D output, as represented by patents. Moreover, all variables are normalized by population.

By solving for the steady state values of the variables in a way consistent with the data, this section provides the punctual estimates for the basic/applied R&D productivity parameters, λ_0 and λ_1.

Chapter 2 estimated λ_0 and λ_1 by solving for λ_0 and λ_1 the steady-state equations of the model. Here we adopt basic research expenditure (available every year) as a proxy for the labor employed in basic research. The real expenditure on basic research is adopted as a proxy for the labour employment in basic research. Since basic research is conceived as the research which is necessary to develop future product innovation, but lacking in currently marketable applications, here it is assumed that the measure of industry performed basic research is negligible. The source of the data is the National Science Foundation, Science and Engineering Indicators (2006). Figure 10 summarizes the trend of the relative basic/applied research productivities punctually estimated by measuring the publicly run basic research as the total basic research expenditure net of the industry performed basic research (ENIPerf).

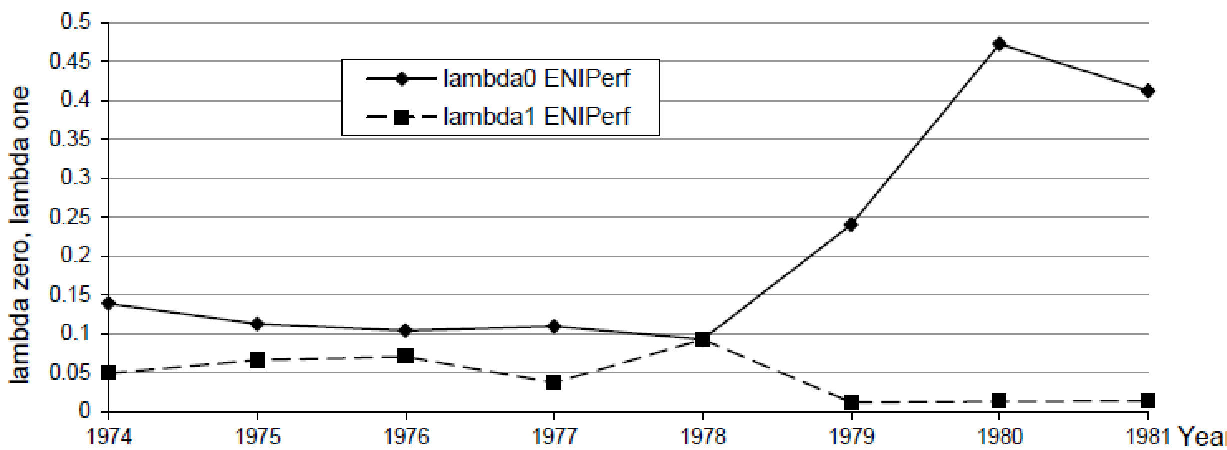


Figure 10: Estimated Basic and Applied Research Productivity
Computed using the Real Basic R&D Expenditure
(Total Basic R&D expenditure net of the Industry performed R&D)
US data from 1974 to 1981

The following Figure 11 depicts the dynamics of the US innovation through the period: it is striking to note how at the beginning of the period most sectors engaged basic research, while at the end of the period the situation had completely reverted.

Estimates Robustness

The robustness of the estimates was tested under two kinds of perturbation: data and parameters.

The NSF Science and Engineering Indicators publishes data on the number of doctorate holders from 1973 every two years. Chapter 2 punctually estimated λ_0 and λ_1 by solving for the steady-state values of the variables in a way consistent with these data.

Here basic research expenditure (available every year) is used as a proxy for the labor employed in basic research.

Table 3 reports the data and the parameters utilised and their sources.

The following figures 12 and 13 show the new estimates carried out by employing the data on the total basic research expenditure net of the industry performed basic research (ENIPerf) and the data on the total basic research expenditure net of the industry funded basic research (ENIFund). The reader can verify as the estimates do not change significantly as a consequence of such perturbation.

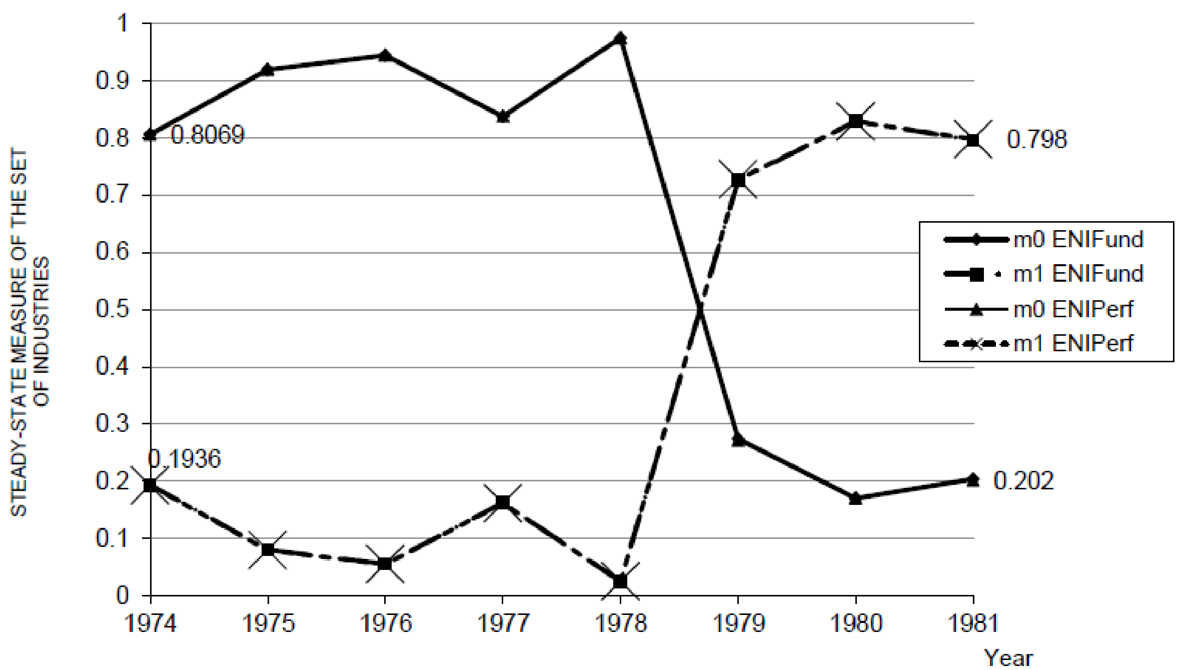


Figure 11: Steady-state mass of sectors performing basic or applied research US data from 1974 to 1981

Finally, the Figures 14 and 15 show the variations of the punctual estimates as a result of different values of the congestion parameter according to the different measures of basic research expenditure. The reader can notice that, even if is characterized by a larger variability, the pattern of both series appears to be remarkably similar.

Table 3: Data and Parameters

Variable or Parameter	Value	Source
Mark-up	1.68	Roeger (1995) and Martins et al. (1996)
R&D congestions	0.3	Jones and Williams (1998) and (2000)
Skilled Labour	Data	U.S. Census, Current Population Survey
Unskilled Labour	Data	U.S. Census, Current Population Survey
Skilled Share in Manufacturing	0.1	Assumption
Labour Force	Data	BUREAU OF LABOR STATISTICS, Labor Force Statistics from the Current Population Survey
Basic R&D Expenditure (ENIPerf)	Data	NSF Science & Engeneering Indicators 2005
Basic R&D Expenditure (ENIFund)	Data	NSF Science & Engeneering Indicators 2005
Skilled wage	Data	Mean income in current dollars, College 4 Years or More, U.S. Census Bureau, Current Population Survey, Annual Social and Economic Supplementsts
Innovation rate	Data	Patents data from the USPTO
Basic Research Productivity	Estimation	
Applied Research Productivity	Estimation	

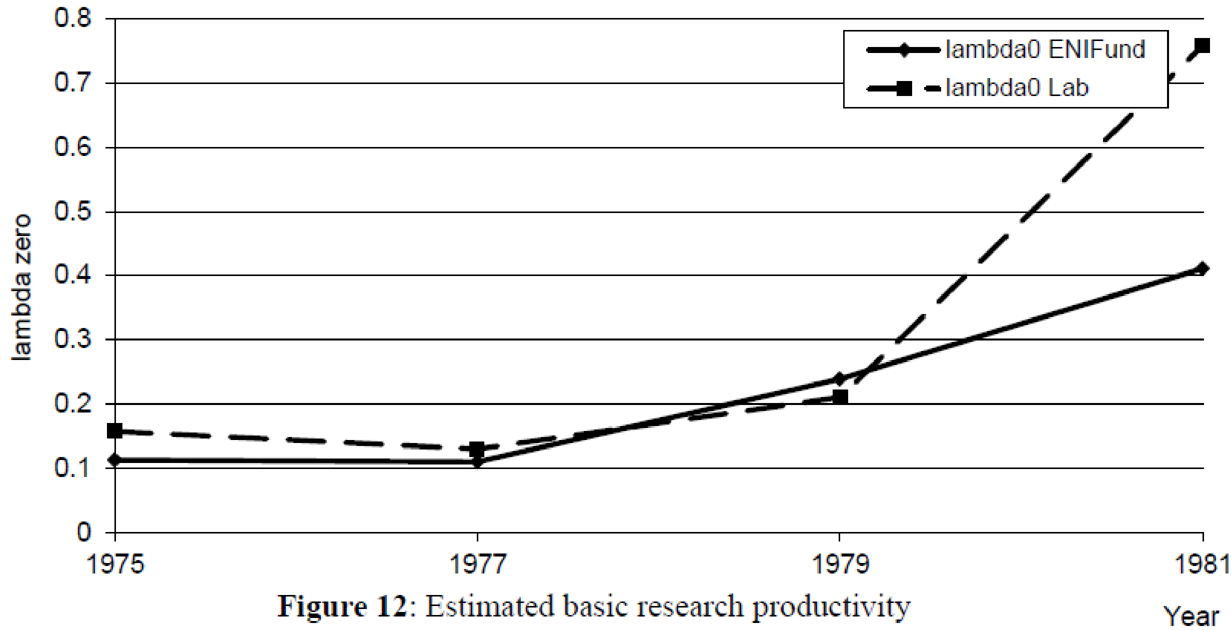


Figure 12: Estimated basic research productivity

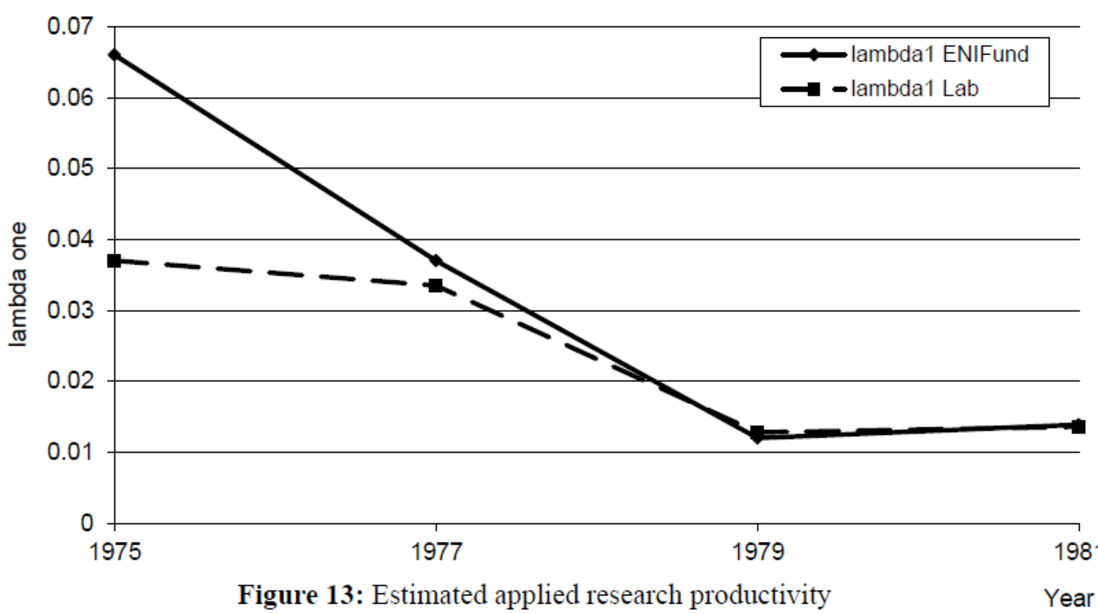


Figure 13: Estimated applied research productivity

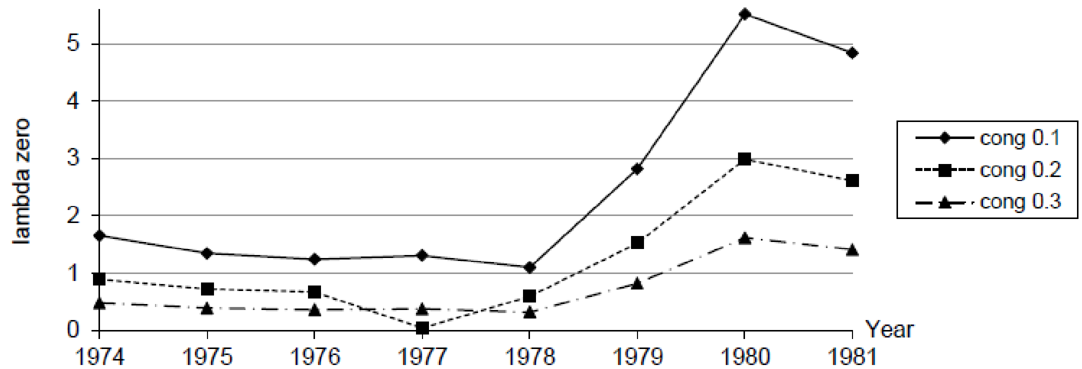


Figure 14: Robustness to perturbation of the intra-sector congestion parameter
Basic research productivity estimates

Computed using the Real Basic R&D Expenditure
(Total Basic R&D expenditure net of the Industry performed basic R&D)

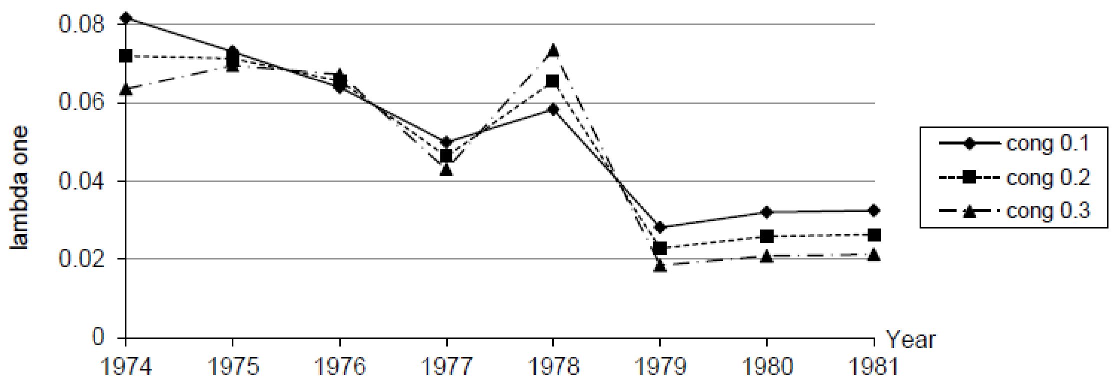


Figure 15: Robustness to perturbation of the intra-sector congestion parameter
Applied research productivity estimates

Computed using the Real Basic R&D Expenditure
(Total Basic R&D expenditure net of the Industry performed basic R&D)

Patent Policy Assessment

To foster innovation and growth should basic research be publicly or privately funded? This section tests Chapters' 2-3 results on the desirability of the US policy shift in view of the estimates just obtained with the new data. Recall that the procedure to compare the innovative performance is made up of four stages, namely:

1. the FIRST STEP plugs the estimated values $\hat{\lambda}_0$ and $\hat{\lambda}_1$ as exogenous variables into the system of equations characterizing the steady-state equilibrium of the hypothetical scenario with patentable basic research and also computes the steady-state equilibrium mass of skilled labour employed in basic research;

2. the SECOND STEP, using the endogenously determined (in the first step) steady-state equilibrium mass of skilled labour employed in basic research, evaluates the innovative performances of the free basic research policy scenarios;

3. the THIRD STEP uses the estimated values $\hat{\lambda}_0$ and $\hat{\lambda}_1$ as exogenous variables in the system of equations characterizing the steady-state equilibrium of the hypothetical scenario with research exemption, and evaluates the impact of reach-through claims/research exemption in terms of innovation rate. It also computes the steady-state equilibrium mass of skilled labour employed in basic research;

4. the FOURTH STEP, using the endogenously determined (in the third step) steady-state equilibrium mass of skilled labour employed in basic research, evaluates the innovative performances of the free basic research policy scenarios against the research exemption scenario.

The following Figure 16 shows the result of comparing the patentable and the unpatentable research tool scenarios. The data confirm the previous result that maintaining free access to basic research findings would have been better for innovation despite the inefficiency of the public laboratories and universities.

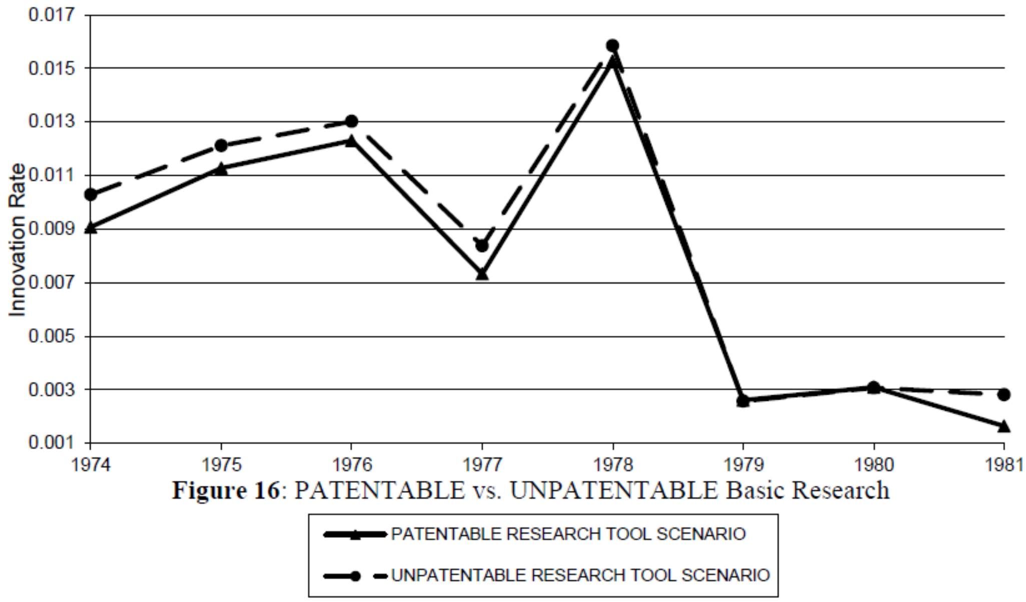


Figure 16: PATENTABLE vs. UNPATENTABLE Basic Research

Figure 17 shows the result of comparing the research exemption and the unpatentable research tool scenarios. In this case it is not so easy to confirm the previous assessment. In fact during the Seventies, no clear winner between the safe harbour exemption and the unpatentable research tool scenarios emerges.

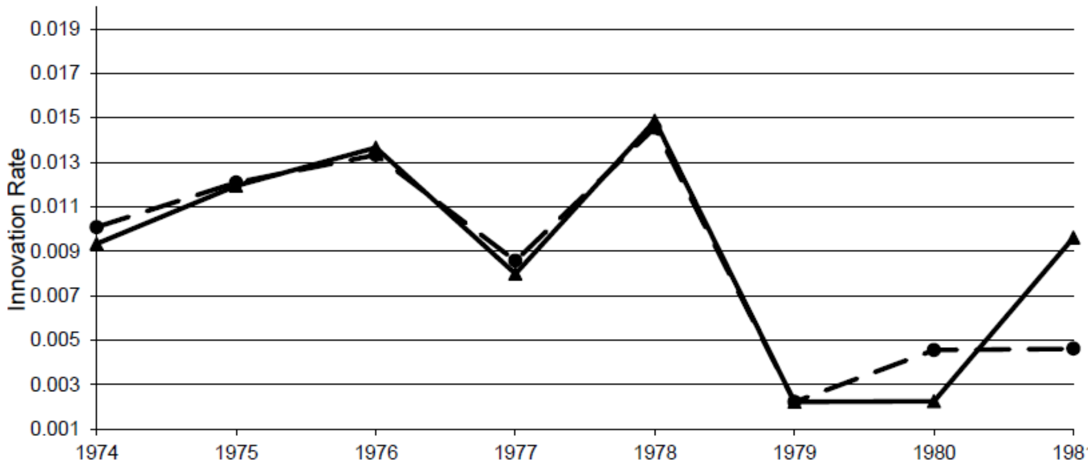
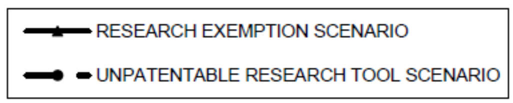


Figure 17: RESEARCH EXEMPTION vs UNPATENTABLE Basic Research



4.4 Conclusions

The debate on the effects of the patentability of research tools on the incentives to innovate is still very controversial, not only in the US but also in Europe and in other important areas of the world. The previous Chapters 2-3 analysed from a general equilibrium perspective the US policy shift towards the extension of patentability to research tools and basic scientific ideas that took place around 1980. These normative innovations have been modifying the industrial and academic lives in the last three decades, raising doubts on their desirability. The losses from the monopolization of applied research induced by intellectual property of research tools have been compared with the inefficacy of public research institutions to promptly react to downstream market opportunities.

Since results are not a priory unambiguous, this chapter used additional available data to calibrate and simulate the model in order to check if the US did it right in changing their institutions around 1980. Overall, the data largely confirm the results previously obtained with a different dataset: maintaining free access to basic research findings would have been better for innovation despite the inefficiency of the public laboratories and universities. The extension of the basic model to incorporate research exemptions and reach-through licensing, looks more ambiguous.

Chapter 5

Upstream Innovation Protection: Common Law Evolution and the Dynamics of Wage Inequality

5.1 Introduction

As is well known, the US economy in the 1980s witnessed the following phenomena:

1. A sustained increase in the skill premium;
2. A sustained increase in the educated fraction of the population;
3. A strengthening of the intellectual property of upstream research[1].

Points 1 and 2 were extensively examined within the macroeconomics debate (see Acemoglu 2002a for an excellent review), and have motivated explanations based on directed change, globalization, and government procurement. Acemoglu (1998 and 2002b) and Kiley (1999) showed that education increases the market for the skill complementary inputs, thereby driving up the profitability of innovations that increase the productivity of the skilled and therefore the returns to higher education. Dinopoulos and Segerstrom (1999) showed that the decrease in trade barriers, by enlarging the market size for suc-

[1] "Upstream" is meant to incorporate basic research and early stage development process.

cessful innovation, increases the return to education. This is so because skilled labour is used more intensively in the knowledge creation activities. Sener (2001) reinforced this channel in the presence of unskilled Schumpeterian unemployment. Cozzi and Impullitti (2009) document a progressive a change in the US government expenditure towards a bigger share of high technology goods; this may have increased the profits of the technologically more dynamic sectors, thereby increasing the returns to college. The aim of this chapter is to assess the potential marginal importance of point 3.

In the recent US history the patent system registered an explosion of upstream patents[2] (Heller and Eisemberg, 1998; Jensen and Thursby, 2001; National Research Council, 2004). Upstream discoveries waiting for an industrial application slowly gained more and more weight as the developers of research tools should considerate the 'reach-through' claims covering their research agendas. Such reach-through claims place a prime value on the research tools underlying the final innovations, enabling the patentee to secure a greater stake in the downstream development and sales.

In order to provide new insights on the links between intellectual property, innovation, education and inequality, this chapter combines a closed-country version of Dinopoulos and Segerstrom's (1999) dynamic general equilibrium model with cumulative innovation and educational choice, with a two-stage cumulative innovation structure *à la* Grossman and Shapiro (1987) and Green and Scotchmer (1995). Basic and applied research technologies are heterogeneous and the bargaining power of the upstream innovation changes[3], thus stylizing the evolution of the US jurisprudence after 1980. From that date on, the US national system of innovation has been re-shaped by a sequence of important new laws and by a cumulative sequence of sentences that set the precedents for future modifications in the jurisprudence. All these changes pointed to an increase in the appropriability of innovations at their initial stages[4]. The pro-early innovation cultural change

[2]Jensen and Thursby's (2001) empirical study found that the majority of the inventions licensed by US universities in 2001 were in an embryonic stage of development ("no more than a proof of concept").

[3]Our framework somewhat complements Eicher and García-Peñalosa, (2008), that envisages endogenous IPR based on firm choice, instead of on jurisprudence evolution.

[4]Including the Stevenson-Wydler act of 1980 and the Bayh-Dole act, of 1980, amended the patent

is also reflected in the increasing protection of trade-secrets - starting in the 80s with the Uniform Trade Secret Act and culminating with the Economic Espionage Act of 1996[5] - as well as in the increasingly positive attitude towards software patents (Hunt, 2001, Hall, 2009), culminating in the Final Computer Related Examination Guidelines issued by the *USPTO* in 1996.

Being the US a common-law regime, the jurisprudence evolved gradually[6] in the direction of stricter intellectual protection of research tools, basic research ideas[7], etc. This process took a quarter century, culminating in the 2002 *Madey vs. Duke University* Federal Circuit's decision, which completed a process of elimination of the "research exemption" to patent claims. This chapter conjectures that, along with other factors, it may have contributed to lead the economy along a transition characterized by increasing wage inequality and higher education attainments and innovation, after an initial productivity slowdown. Interestingly, the more recent cases seem to be witnessing an opposite trend, most notably *Merck vs Integra Lifesciences* (2005), in which the Supreme Court decided to re-affirm research exemption in the pharmaceutical sector.

The US legal system, as the legal systems of most of the Commonwealth countries, includes in the list of the sources of right the common law. The essence of the common law is that it is made by judges sitting in courts, by applying their common sense and knowledge of legal precedent (*stare decisis*) to the facts before them. It is founded on the concept of precedence on how the courts have interpreted the law: under common law the decisions are reached by analogy, after comparing the facts of a particular case to similar previous cases. During the early 1980s began a progressive process in which the

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law, to facilitate the commercialization of inventions obtained thanks to government funding, especially by universities.

[5]See Cozzi (2001) and Cozzi and Spinesi (2006).

[6]In our case, it is important to recall Janice Mueller's (2004) account of the common law development of a narrow experimental use exemption from patent infringement liability: with special reference to the discussion of the change in the doctrine from 1976's *Pitcairn v. United States*, through 1984's Federal Circuit decision of *Roche Products, Inc. v.Bolar Pharmaceutical Co.,* all the way to *Madey v. Duke University* in 2002.

[7]See Gallini (2002), Mueller (2001 and 2004), Scotchmer (2004).

U.S. Court decisions changed from the old doctrine limiting the patentability of early-stage scientific discoveries to the conception that also fundamental basic scientific findings (such as genetic engineering procedures or semiconductor designs) are patentable. Ideally started in 1980 with the *Diamonds vs. Chakrabarty* case, in which the Supreme Court of United States ruled that microorganism produced by genetic engineering could be granted patent protection, according to some authors, this process culminated in 2002 with the well-known Federal Circuit decision *Madey vs. Duke University*, by which the common law fair use doctrine did not even allow universities to infringe patents on research tools for teaching or experimental purposes (Mueller, 2004).

If what deeply characterizes common law (and sharply separates it from the Continental Europe type legal systems) is an uninterrupted continuity such that within the *stare decisis* regime an institutional break point is even hardly conceivable, we must conclude that the analysis of the effects of the US patent policy on the economy is forced to include the whole transition dynamics. In other words, if the common law shows a strong link with its evolutionary history, we are not dealing anymore with an IPR revolution but with its evolution. Hence, the cumulated stock of courts decisions up to time t determines a flow of new decisions, or, the court's orientation in a given instant of time t depends on the cumulated stock of sentences up to time t. The law and economics literature is currently modelling the evolution of the case law in the perspective of analysing Benjamin Cardozo's and Richard Posner's view of common law as efficiency promoting. In fact, according to this influential view, unlike civil law, being the common law decentralized, it follows the aggregate decision making of several heterogeneous judges, whose idiosyncratic opinions average one another. Moreover, the very sequential precedent structure, implies that (Gennaioli and Shleifer, 2007b) one appellate court overrules another's decision, tending to progressive mitigation and efficiency only if the majority of the judges is unbiased, depending also on the judge's effort cost of changing the legal rule established in a precedent. Appellate courts may change a previously established legal rule also by "distinguishing" the case based on the consideration of a "previously neglected dimension" (Gennaioli and Shleifer, 2007a), which can facilitate convergence towards a more efficient legal rule. Empirical analysis is still scarce, with the notable exception of Niblett, Posner, and Shleifer's (2008) analysis of the evolution of the Economic Loss Rule (ELR) in the US construction industry from 1970 to 2005, according to which the ELR doctrine seemed to follow a clear increasingly narrow pattern for more than two decades (1970-1993), which was then followed by a subsequent (1994-2004) inverse trend. Based on these analyses, we inquire on whether the increasingly pro-upstream R&D court orientation from 1980 to 2002 has been following an improvement in promoting innovation or if it has ended up following the bias of less and less liberal judges. This chapter looks for potentially detectable aspects of the time series of several important variables - skill wage premium, education, innovation, labour force allocation, market value of patents, etc. - associated with either long-term evolution of the legal rules. The argument here follows a dynamic general equilibrium perspective, which forces us to assume that economic agents are sufficiently intelligent to detect what "trend" is occurring, and suitably take optimizing decisions.

Analysing the effects of an expected and progressive change in the patent protection of basic research entails to simulate the trajectories of all variables in their transitional dynamics. Hence this work extracts lessons from the numerical results, useful to detect whether an increasingly more strong basic research protection common law doctrine is gradually facilitating the national system of innovation or evolving for the worse.

The remainder of the chapter is organized as follows. Sections 5.2 and 5.3 set the model. Section 5.4 characterizes the equilibrium. Section 5.5 focusses on the growth maximizing steady-state upstream innovator share in a simple special case, useful as a benchmark. Section 5.6 shows the numerical simulations. Section 5.7 concludes. Most of the algebra is relegated to the Appendix.

5.2 The Model

5.2.1 Households

Assume a large number of dynastic families, normalized to 1 for simplicity, whose members, born at birth rate $\tilde{\beta}$ and passing away at rate δ, live a period of duration D. The resulting population growth rate[8] is $g = \tilde{\beta} - \delta > 0$. This demographic structure implies the following restrictions: $\tilde{\beta} = \frac{ge^{gD}}{e^{gD}-1}$ and $\delta = \frac{g}{e^{gD}-1}$.

At time t the total number of individuals is e^{gt}. Each individual can spend her life working as unskilled or studying the first $T_r < D$ periods and then working as skilled. Each individual cares only about the utility of the average family member. Hence, despite bounded individual life, the individual decisions are taken within the household by maximizing the following intertemporally additive utility functional:

$$U = \int_0^\infty e^{-\rho t} u(t)\, dt, \tag{5.1}$$

where $\rho > 0$ is the subjective rate of time preference. Per-family member instantaneous utility $u(t)$ is defined as:

$$u(t) = \int_0^1 \ln \left[\sum_j \gamma^j d_{jt}(\omega) \right] d\omega, \tag{5.2}$$

where $d_{jt}(\omega)$ is the individual consumption of a good of quality $j = 1, 2, ...$ (that is, a product that underwent j quality jumps) and produced in industry ω at time t, and bought at price $p_{jt}(\omega)$. Parameter $\gamma > 1$ measures the size of the quality upgrades.

Defining per-capita expenditure on consumption goods as $E(t) = \int_0^1 \left[\sum_j p_{jt}(\omega)\, d_{jt}(\omega) \right] d\omega$, the real interest rate as $i(t)$, and time 0 family wealth as $W(0)$, the intertemporal budget

[8] Dinopoulos and Segerstrom (1999) have first developed the overlapping generations education framework followed here. Boucekkine et al. (2002) and Boucekkine et al. (2007) recently studied population and human capital dynamics in continuous time and off steady states and numerically calibrated in a way methodologically more similar to ours.

constraint is $\int_0^\infty e^{gt-\int_0^t i(\tau)d\tau} E(t)\,dt \leq W(0)$.

Following standard steps of quality ladders models[9], the consumers will only buy good with the lowest quality adjusted price, and the Euler equation follows:

$$\dot{E}(t)/E(t) = i(t) - (\rho + g) = r(t) - \rho, \tag{5.3}$$

where $r(t) \equiv i(t) - g$ is the population growth deflated instantaneous market interest rate at time t, and, together with the transversality condition, determines consumer choice.

Individuals differ in their learning ability θ, which, for each generation, is uniformly distributed in the unit interval. Hence an individual of ability $\theta \in [0, 1]$ will be able to acquire $\theta - \Gamma$ units of human capital after an indivisible training period of length T_r. The only cost of education is the individual's time, which prevents her from earning the unskilled wage w_u. In what follows we choose unskilled labour as our numeraire, and therefore set $w_u(t) = 1$ at all $t \geq 0$.

Hence an individual born at t with (known) ability $\theta(t) \in [0, 1]$ and who decides to educate herself will earn nothing from t to $t + T_r$, and then earn a skilled wage flow $(\theta(t) - \Gamma)w_H(s)$ at all dates $s \in [t + T_r, t + D]$, which implies that at time t there will exist an ability threshold $\theta_0(t) \in [\Gamma, 1]$ below which the individual decides to work as an unskilled. Threshold $\theta_0(t)$ solves the following equation:

$$\int_t^{t+D} e^{-\int_t^s i(\tau)d\tau} ds = (\theta_0(t) - \Gamma) \int_{t+Tr}^{t+D} e^{-\int_t^s i(\tau)d\tau} w_H(s) ds, \tag{5.4}$$

obtaining

$$\theta_0(t) = \Gamma + \frac{\int_t^{t+D} e^{-\int_t^s i(\tau)d\tau} ds}{\int_{t+Tr}^{t+D} e^{-\int_t^s i(\tau)d\tau} w_H(s) ds}. \tag{5.5}$$

It is important to notice that the ability threshold can change over time, because the future real interest rates $i(t)$ and skilled wage rates $w_H(t)$ are free to change. It is

[9] See Segerstrom et al. (1990), Grossman and Helpman (1991) and Segerstrom (1998).

worthwhile to notice that Dinopoulos and Segerstrom's (1999) framework allows for a strong dispersion within the skilled labour group: in fact, $w_H(t)$ is the amount of skilled wage per-efficiency unit of labour, whereas people actual earnings vary with their ability.

Since in a steady state $i(t) = \rho + g$, the steady state level of $\theta_0(t)$ is

$$\theta_0 = \Gamma + \frac{1 - e^{-(\rho+g)D}}{\left[e^{-(\rho+g)Tr} - e^{-(\rho+g)D}\right] w_H}, \tag{5.6}$$

where w_H denotes the steady state skill premium.

5.2.2 Manufacturing

In each final good industry $\omega \in [0,1]$ and for each quality level $j(\omega)$ of the good, production is carried out according to the following Cobb-Douglas technology

$$y(\omega, t) = X^{\alpha}(\omega, t) M^{1-\alpha}(\omega, t), \text{ for all } \omega \in [0,1], \tag{5.7}$$

where $\alpha \in (0,1)$, $y(\omega, t)$ is the output flow at time t, $X(\omega, t)$ and $M(\omega, t)$ are the skilled and unskilled labour inputs. In each industry firms minimize costs by choosing input ratios

$$\frac{X(\omega)}{M(\omega)} = \frac{1}{w_H(t)} \frac{\alpha}{1-\alpha}. \tag{5.8}$$

The total per-capita amount M of unskilled labour only works in the manufacturing sectors. Therefore the aggregate skilled labour demand is equal to:

$$X(\omega, t) = \frac{1}{w_H(t)} \left(\frac{\alpha}{1-\alpha} \right) M(t) P(t) \tag{5.9}$$

In per-capita terms,

$$x(\omega, t) \equiv \frac{X(\omega, t)}{P(t)} = \frac{1}{w_H(t)} \left(\frac{\alpha}{1-\alpha} \right) M(t) \equiv x(t). \tag{5.10}$$

As in Aghion and Howitt (1992), skilled labour can also work in the R&D sectors. Therefore, a higher skilled premium $w_H(t)$ frees resources for the R&D sectors.

Assume instantaneous Bertrand competition in all sectors, since only the owner of the most recent top quality good patent can produce the top quality version of its sector good, the equilibrium price will be equal to a mark-up $\gamma > 1$ over the unit cost $c(w_H(t), 1)$. Moreover, being demand unit elastic, per-capita demand is $d(t) = \frac{E}{\gamma c(w_H(t),1)}$. Therefore is each sector the temporary monopolist who owns the top quality product patent earns the same profit which, in per-capita terms, is equal to[10]:

$$\begin{aligned} \pi(t) &= \frac{\gamma - 1}{\gamma} E(t) = (\gamma - 1) \frac{w_H(t)x(t)}{\alpha} = \\ &= (\gamma - 1) \frac{1}{1 - \alpha} m(t). \end{aligned} \tag{5.11}$$

5.3 R&D and Innovation

The quality level j of each final product of variety $\omega \in [0, 1]$ can increase as a result of R&D undertaken by private firms. In order to capture the interaction between basic and applied research[11], we assume - as in Chapters 2-4 - that a basic research idea is a prerequisite to applied research and applied R&D success opens the door for a further basic research advance. Hence, the innovative process leading to a final product quality is, as in Grossman and Shapiro (1987), a two-stage process: in the first stage R&D discovers a pure idea; in the second stage R&D embodies that idea into a new product. The first stage - basic research - of the product quality jump is the outcome of a Poisson process

[10] The second equality builds on the Cobb-Douglas property that minimum total cost is $\left[\left(\frac{1-\alpha}{\alpha}\right)^{-(1-\alpha)} + \left(\frac{\alpha}{1-\alpha}\right)^{-\alpha}\right] w_s^{\alpha} w_u^{1-\alpha} X^{\alpha}(\omega) M^{1-\alpha}(\omega)$. Hence profit is $(\gamma - 1)$ times total cost. Using eq. (5.9) and simplifying gives the result.

[11] According to Nelson (1959) and (2006), basic R&D is not only a source of inspiration for applied R&D, but also continuously inspired by applied R&D, which raises important questions on why some new discoveries actually work. This second point is also modelled by Howitt (1999), when knowledge frontier advances are a result of applied R&D success frequencies.

with probability intensity $\frac{\lambda_0}{P(t)}\left(\frac{N_B(\omega,t)}{P(t)}\right)^{-a}$ per unit of research labour, where $\lambda_0 > 0$ is a basic research productivity parameter, $N_B(\omega, t)$ is the mass of research labour employed in sector ω at time t, and $a > 0$ is a congestions externality parameter. The presence of population size, $P(t)$, in the denominator states that R&D difficulty increases with the total population in the economy[12], which delivers endogenous growth without the strong scale effect[13], as suggested by Smulders and Van de Klundert (1995), Young (1998), Peretto (1998 and 1999), Dinopoulos and Thompson (1998), Howitt (1999), and recently confirmed empirically by Ha and Howitt (2006) and Madsen (2008).

The second stage - applied research - completes the basic research idea and generates the new higher quality producible good according to a Poisson process with probability intensity $\frac{\lambda_1(t)}{P(t)}\left(\frac{N_A(\omega,t)}{P(t)}\right)^{-a}$ per unit of research labour, where $\lambda_1(t) > 0$ is an applied research productivity, viewed by the firms as a constant; $N_A(\omega, t)$ is the mass of research labour employed in sector ω at time t; and $a > 0$ is the congestions externality parameter.

Defining $n_B(\omega, t) \equiv \frac{N_B(\omega,t)}{P(t)}$ and $n_A(\omega, t) \equiv \frac{N_A(\omega,t)}{P(t)}$, as the skilled labor employment in each basic and, respectively, applied R&D sector, we can express the expected innovation rate in a ω' sector undertaking only basic R&D as $\lambda_0 n_B(\omega', t)^{1-a}$ and the expected innovation rate in a ω'' sector undertaking only applied R&D as $\lambda_1(t)n_A(\omega'', t)^{1-a}$. All stochastic processes are independent both across sectors and across firms. Hence, the existence of a continuum of sectors implies that the law of large number applies and aggregate variables evolve deterministically. Since all sectors switch from hosting only basic R&D firms - belonging to subset $A_0(t) \subset [0, 1]$ - to hosting only applied R&D - belonging to subset $A_1(t) \subset [0, 1]$ - the mass of sectors belonging to each type will flow deterministically[14]. Notice that $A_0(t) \cup A_1(t) = [0, 1]$ and $A_0(t) \cap A_1(t) = \emptyset$. Moreover, in our model, symmetric equilibria exist, allowing us to simplify notation: $n_B(\omega, t) \equiv n_B(t)$ and $n_A(\omega, t) \equiv n_A(t)$. Therefore, if $m(A_0(t)) \in]0, 1[$ is the Lebesgue mass of the $A_0(t)$

[12] Population density favour innovation at the local level (see Carlino, Chatterjee and Hunt, 2001): according to this solution to the strong scale effect, the dilution of R&D is not related to population density, but with the overall size of the economy.

[13] See Dinopoulos and Thompson (1999) and Jones (2005).

[14] Provided the initial mass Lebesgue mass of each was positive.

subset - and hence $m(A_1(t)) = 1 - m(A_0(t))$ the Lebesgue mass of $A_1(t)$ subset - its evolution would be deterministic and described by the following first order differential equation:

$$\frac{dm(A_0(t))}{dt} = (1 - m(A_0(t)))\, \lambda_1(t)\, (n_A(t))^{1-a} - m(A_0(t))\lambda_0\, (n_B(t))^{1-a}. \qquad (5.12)$$

In order to truly capture the distinction between pioneering and follow-on innovations, in this chapter - unlike in the previous ones - we follow the literature, by thinking of pioneering inventions as ones that generate more spillovers or are in some sense "more important" than the subsequent follow on innovations. We assume that the aggregate output of basic research increases the productivity of applied research: $\lambda_1(t) = \overline{\lambda}_1 \left(1 + \lambda_0 \left[\int_0^1 n_B(\omega, t) d\omega\right]^{1-a}\right)^{\varphi}$, where $\overline{\lambda}_1$ and φ are positive constants. This formulation introduces the possibility of cross-fertilization of applied research by other sector's basic research findings[15]. In symmetric equilibrium $\lambda_1(t) = \overline{\lambda}_1 \left(1 + \lambda_0 \left[n_B(t)\right]^{1-a}\right)^{\varphi}$.

We assume free entry into basic and applied research. Each inventor, be she basic or applied, is granted a patent. However, though the first R&D firm that invents a new final product gets the patent anyway, it will infringe the patent held by the previous basic research inventor. Therefore it will have to bargain with the basic research patent holder in order to produce the new version of this good.

The share, $\beta(t) \in]0, 1[$, of the final product (applied) patent value assigned - at the end of the negotiations taking place at time t - to the upstream (basic) patent holder[16] captures time t court orientation towards intellectual property. New laws, patent law amendments, changes in the jurisprudence towards stronger patent claims and weakening

[15] This is complementary to Howitt's (1999) assumption of general knowledge, $A_t^{\max}$, being positively affected by the aggregate applied R&D.

[16] Assuming that basic and applied innovators matched and targeted applied innovator-specific innovations, could re-read this strategic interaction as Aghion and Tirole's (1994a and b) research unit (RU) and customer (C). Then our case would clearly correspond to when RU's effort is important ($\tilde{U}_C > U_C$), which implies that "the property right is allocated to RU" (Aghion and Tirole, 1994b, p. 1191). In this light, our $\beta(t)$ generalizes Aghion and Tirole's (1994a and b) equal split assumption.

research exemptions would correspond to increases in $\beta(t)$, whereas a gradually looser upstream patent holder protection and stronger research exemptions would correspond to a declining $\beta(t)$. In the rest of the paper we will consider gradual changes in patent policy in terms of the sign of $\dot{\beta}(t)$. In fact, we assume that the following holds:

$$\dot{\beta}(t) = (1 - \psi)(\bar{\beta} - \beta(t)). \tag{5.13}$$

Equation (5.13) is a linear differential equation with constant coefficient, which describes the speed of change in $\beta(t)$ per unit time. Parameter $\psi < 1$ guarantees asymptotic stability and $\bar{\beta} \in]0,1[$ is the steady state. We will consider the progressive tightening of intellectual property rights in the US as the result of a sudden change in $\bar{\beta}$, which determines a gradual increase in $\beta(t)$ from its previous lower steady state level to its new level. It is important to notice that we are in a rational expectation framework: all economic agents after the regime change can predict the successive increases in $\beta(t)$, and the transition to a tight IPR regime is known to the agents from the beginning and all decisions are re-optimized. Hence all our numerical simulations are immune to Lucas' critique, unlike other models that, albeit assuming dynamic general equilibrium, treat the gradual policy changes as a sequence of surprises. The reason why we think our approach is appropriate is that from 1980 on IPR policy has steadily and progressively been tightening and progressively become more and more biased toward earlier innovator. This steady upstream shift of innovation incentives was too regular not to be incorporated in people's expectations[17], which leads law scholars to view 1980 as a sort of structural break of equation (5.13), and forces us to study the whole transitional dynamics of the model's economy. The statutory decisions taken in the early 1980 triggered a gradual change in the common law[18]. Maybe such exogenous technological-scientific modifications were taking place which imposed statutory intervention to change an otherwise binding

[17] Unless focussing attention only on a short time span, as in Chapter 2.

[18] According to Fon and Parisi (2006), such a case evolution could also appear in a civil law system.

set of precedents[19]: this has inaugurated the new era, which would be represented by an increase in $\bar{\beta}$ and a resulting re-adjustment of the judicial system, thereby dragging the whole economy.

5.4 Equilibrium

In this section we keep time notation, because, since we are considering dynamic general equilibrium, all endogenous variable can change over time, as will be shown in the numerical simulations.

Let us define v_B,v_L^0, and v_L^1 as the present expected value of a basic research patent (v_B), of an A_0 industry quality leader (v_L^0), and of an A_1 industry challenged leader (v_L^1).

Costless arbitrage between risk free activities and firms' equities imply that in equilibrium at each instant the following equations shall hold:

$$w_H(t) = \lambda_0 n_B(t)^{-a} v_B(t) \tag{5.14a}$$

$$r(t)v_B(t) = \lambda_1(t) n_A(t)^{1-a} \left(\beta(t) v_L^0(t) - v_B(t)\right) + \frac{dv_B(t)}{dt} \tag{5.14b}$$

$$w_H(t) = \lambda_1(t) n_A(t)^{-a} \left(1 - \beta(t)\right) v_L^0(t) \tag{5.14c}$$

$$r(t)v_L^0(t) = \pi(t) - \lambda_0 n_B(t)^{1-a} \left(v_L^0(t) - v_L^1(t)\right) + \frac{dv_L^0(t)}{dt} \tag{5.14d}$$

$$r(t)v_L^1(t) = \pi(t) - \lambda_1(t) n_A(t)^{1-a} v_L^1(t) + \frac{dv_L^1(t)}{dt} \tag{5.14e}$$

The value of a monopolist in an A_0 industry, v_L^0, has to obey equation (5.14d): in fact, the shareholders of the current quality leader compare the (population growth adjusted) risk free income, rv_L^0, obtainable from selling their shares and buying risk free bonds

[19] "Second, it may be impossible to reverse the precedents of the past when changing economic conditions warrant such a reversal. Precedent tends to weigh heavily upon decisions of the court, as perhaps it should. But rulings of a century ago, say on questions of pollution, may not be optimal today. If the bias imparted by precedent is too great, however, a change in precedent may be impossible, even if it would be beneficial to many parties involved" (Goodman, 1978, p. 406).

to the expected value of their profits, π, net of probable capital loss, $\lambda_0 n_B^{1-a}\left(v_L^0 - v_L^1\right)$, in case a new basic research result appears in the industry. Since we assume perfect and costless financial markets, all idiosyncratic risk is diversified away and investors only compare expected returns.

As soon as a new basic R&D result appears in the industry, the incumbent monopolist's value falls down to a lower, but still positive, value v_L^1, which has to obey equation. (5.14e): as before, risk free income is equated to expected profits net of expected capital loss, but now the probability of the basic research idea's being completed by applied research in the industry, $\lambda_1 n_A^{1-a}$, is the monopolistic profit hazard rate, as the arrival of the new final product implies the complete displacement of the current leading edge product.

Equation (5.14a) characterizes free entry into basic R&D (in an A_0 industry), equalizing the skilled wage to the probability $\lambda_0 n_O^{-a}$ of inventing times the value v_B of the resulting patent.

Equation (5.14b) equated the risk free income from selling a basic R&D patent, rv_B, to the expected present value of holding it in an A_1 industry. These expected increase in value deriving from someone else's - the n_A downstream researchers' - discovering the industrial application, of value v_L^0, plus the gradual appreciation in the case of someone else's R&D success not arriving, $\frac{dv_B}{dt}$.

Equation (5.14c) is the free entry condition for downstream completers that rationally expect to appropriate only fraction $1-\beta$ of the value of the final good monopolist.

As in the previous section, the industrial dynamics of this economy is described by the following first order ordinary differential equation:

$$\frac{dm(A_0(t))}{dt} = \left(1 - m(A_0(t))\right)\lambda_1(t)\left(n_A(t)\right)^{1-a} - m(A_0(t))\lambda_0\left(n_B(t)\right)^{1-a}. \tag{5.15}$$

These equations must be supplemented with the skilled labour market equilibrium condition

$$x(t) + m(A_0(t))n_B(t) + \left(1 - m(A_0(t))\right)n_A(t) = h(t), \tag{5.16}$$

where $h(t) \equiv H(t)/P(t)$ is the aggregate population-adjusted human capital.

5.5 Analysis of a Benchmark Special Case

Though the numerical simulations of Section 6 will illustrate the main properties of our economy, it is useful to provide some qualitative analysis under special parameter conditions. The results of this sections are obtained under the assumption that $\rho = 0$, which greatly facilitates the analytical derivations. Since all steady state equations are continuous in all variables and parameters, the sign of the derivatives of the steady state equilibrium endogenous variables remain unaltered in a positive neighbourhood where $i > 0$. Notice that in the steady state the real interest rate is $i = r + g$, and our assumption implies $i = g > 0$. Hence equations where ρ appears do not formally change[20]. For simplicity, we will also assume $\varphi = 0$: this eliminates the externality of basic research on applied research.

Notice that equation. (5.14b), the steady state definition and $r = 0$ imply:

$$v_B = \beta v_L^0.$$

From this and from equations (5.14a) and (5.14c):

$$n_A = \left(\frac{\lambda_1}{\lambda_0} \frac{1-\beta}{\beta} \right)^{\frac{1}{a}} n_B. \tag{5.17}$$

This confirms Denicolo's (2001) Proposition 1 in our extended framework. From equations (5.14d) and (5.14e), the steady state definition and $r = 0$ we can write:

$$v_L^0 = \left[\left(\frac{\lambda_1}{\lambda_0} \right)^{\frac{1}{a}} \left(\frac{1-\beta}{\beta} \right)^{\frac{1-a}{a}} + 1 \right] v_L^1. \tag{5.18}$$

[20]More generally, even assuming $g = 0$, and therefore $\rho = 0$ would not imply complications, as straightforward application of De L'Hospital's theorem would imply $lim_{\rho \to 0} \theta_0 = \gamma + \frac{D}{(D-Tr)w_H}$.

Imposing the steady state into (5.15) and using (5.17) yields:

Lemma 1 *The steady state equilibrium fraction of industries where basic R&D is active is*

$$m(A_0) = \frac{1}{1 + \left(\frac{\lambda_0}{\lambda_1}\right)^{\frac{1}{a}} \left(\frac{\beta}{1-\beta}\right)^{\frac{1-a}{a}}}. \tag{5.19}$$

Remark. What **Lemma 1** states is that the higher the difficulty of basic research (applied research), i.e. the lower λ_0 (the lower λ_1) the higher the fraction of sectors where basic (applied) R&D is needed.

This has implications for R&D enhancing regulation:

Proposition 1. *The growth maximizing upstream inventor share, β^*, of the final good patent value is equal to:*

$$\beta^* = \frac{\lambda_1}{\lambda_0 + \lambda_1} = \frac{1}{\frac{\lambda_0}{\lambda_1} + 1}. \tag{5.20}$$

Proof. See Appendix.

Remark. Our analysis implies that innovation-maximizing basic research patent claims should be neither too broad nor too narrow. Since in this example time costs nothing, both applied (direct) and basic (indirect) research should be given equal reward if their R&D technologies are the same ($\lambda_0 = \lambda_1$). Interestingly, Green and Scotchmer's (1995) and Scotchmer's (2004) benchmark parameter value is $\frac{1}{2}$, as well as Aghion and Tirole's (1994a and b) equal split assumption. A similar assumption was made by Denicolo's (2001) patentable and infringing second-stage innovation. In our perpetual innovation framework, as ρ increases basic research should be compensated more in order to maximize growth.

Proposition 1 states that the innovators should be rewarded proportionally more in the stages of R&D where innovation is harder to achieve. Plugging β^* into equation. (5.17) implies that at the optimal policy $n_A = n_B$. Hence the optimal share is higher in the (sub-)industries where (equilibrium) innovation is slower - expected times $\frac{1}{\lambda_0 n_B^{1-a}} > \frac{1}{\lambda_1 n_A^{1-a}}$

imply $\beta^* > 0.5$ and viceversa - which is consistent with Hunt's (2004) testable implication for innovation promoting patentability standards[21].

Our analysis is also related to Hunt (2006), in which each duopolist, when obtaining a patent, get a ticket to sue the rival and to grab a share $0 < \beta < 1$ of the value of its innovation. In his model, Hunt proves that if β is relatively too high the increase in patent protection discourages R&D. Here we follow a similar logic, though in a sequential framework: endowed with too much bargaining power, the basic research patent holder may end up capturing a large part of the downstream innovation, thereby discouraging total R&D.

5.6 Numerical Simulations

This section illustrates the representative time trajectories of endogenous variables following the announcement of a regime change in the law of motion of the share of the final value of applied R&D that will be assigned to the basic researcher. This corresponds to a sudden change in the steady state value of equation. (5.13) that gradually drives the system towards the new steady state. Several discrete approximations of the differential equations (5.28), (5.31), (5.13), (5.34), (5.14b), (5.14d), (5.14e), (5.40),(5.41), (5.38), (5.39), (5.15), and cross-equations restrictions (5.14a), (5.14c), (5.10), (5.11), (5.16), and (5.35) were run, obtaining quite regular results.

It is also assumed that in the common law regime the policy/courts orientation change is not only gradual but also expected ahead of time.The following figures show the simulations obtained for the following parameter values: $\alpha = 0.1$, $a = 0.3$, $\gamma = 1.68$, $\lambda_0 = \bar{\lambda}_1 = 1$, $\varphi = 0.01$, $D = 40$, $n = 0.01$, $r = 0.05$, $T_r = 4$, $\Gamma = 0.75$, which are standard in the literature. As for the common law adjustment parameter, we set $\psi = 0.9$. Moreover, no difference in the qualitative and little quantitative difference was associated with

[21] An interesting extension of our paper would be obtained by breaking the symmetry assumption over the product space.

robustness analysis: for example, setting $\varphi = 0$ through $\varphi = 1$ did not change almost anything.

Assume that the economy begins with a steady state associated with a given value of $\bar{\beta}$. Then $\bar{\beta}$ changes and the common law share of the basic research inventor starts to head to its new steady state value.

In order to make different simulations comparable, we plot the trajectories of the deviations of the value of each variable from its initial steady state value, divided by its initial steady state value.

Figure 18 assumes that, after a long term (40 periods) initial value of $\bar{\beta} = 0.35$, it suddenly changes to $\bar{\beta} = 0.5$. As a consequence of Proposition 1, such a change will be beneficial for long term growth.

Such a change is clearly growth improving from a steady state perspective: in the long run the new steady state is characterized by a higher rate of aggregate growth, a higher skill premium, a higher fraction of population choosing to educate themselves ("college students") and a higher aggregate human capital. A higher value of β means a higher fraction of the final invention appropriated by the basic researcher who invented its basic research pre-requisite and a lower value of the final product appropriated by the applied researcher who invented its commerciable version. Therefore basic research is becoming more profitable (higher "Basic Patent Value", v_B) and applied research less profitable. Consequently basic research employment increases - both at the aggregate ("Basic Research") and at the industry, ("Nb") level - and applied research employment decreases both at the aggregate ("Applied R&D") and at the industry, ("Na") level. A consequence of this is that in the long run the stock market value (v_L^1) of an A_1 monopolist increases - as it faces less obsolescence - while the long run the stock market value (v_L^0) of an A_0 monopolist decreases, as it faces more obsolescence. Since the positive incentives to basic R&D outweigh the negative incentives to applied R&D, R&D becomes more profitable and more skilled labour is demanded. Therefore the skill premium, w_H, increases as well as the present discounted value of high skill labour, thereby inducing a larger fraction of the population to enrol at university. This will gradually increase the supply of human capital and decrease the supply of unskilled labour.

In the transitional dynamics, it is important to notice that as the change in the long-term court orientation $\bar{\beta}$ is forecast by the private actors, all the stock variables - $\beta(t)$, $h(t)$, $m(t)$, and $m(A_0(t))$ - are predetermined, and for example, by equation (5.11), $\pi(t)$ is constant. Hence only jump variables such as prices, wages, and employment can change. Being $\beta(t)$ monotonically increasing, the relative incentives of basic versus applied research are gradually changed in favor of basic and to the detriment of applied research. However, the dynamics of $\beta(t)$ interacts with the intrinsically dynamic nature of the R&D process, in a way that is not captured by the mere comparative statics of steady state analysis: in fact, the expectation of higher future values of $\beta(t)$ certainly favours current basic research - the completion of which will take place in the future - without harming current applied R&D with the same intensity. To fix ideas, imagine that basic research takes place in one period, as does applied research: the announcement of a higher β next period does not penalise current applied R&D while instead encouraging current basic research - which is promised a higher share of the future discovery. In our continuous time framework the same effect is at work: the two-stage Poisson process of our Grossman and Shapiro's (1987) framework implies that periods are stochastic in length and meanwhile $\dot{\beta}(t) > 0$ favours the expectedly late fruits of basic research more than it reduces the expectedly earlier gains of applied research. As a consequence, aggregate R&D is favoured, and the increase in the demand for $n_B(t)$ is matched by a lower decrease in the demand for $n_A(t)$, which implies that the difference $m(A_0(t))n_B(t) - [1 - m(A_0(t))]\, n_A(t)$ increases and must be matched by a decrease in $x(t)$: the increase in the net demand for R&D labour can be satisfied only by a decrease in the manufacturing skilled-labour employment. This temporary excess demand for skilled labour is the reason for the immediate increase the skill premium. As time passes, the increase in $w(t)$ will encourage marginally able students to enrol to college, thereby leading to a future increase in the aggregate supply of human capital and to a partially offsetting effect on

$w(t)$. However, as long as $\beta(t)$ keeps increasing, the demand for R&D labour continues to grow, though the decline in $\dot{\beta}(t)$ will eventually correct the previously mentioned intertemporal asymmetry that favoured basic research more than it disincentived applied R&D. Such results are consistent with the conclusions of Waelde (2005) and Waelde and Woitek (2004) which, in a different framework, show how economic fluctuations originate endogenously in the economy and the R&D acts a mechanism to generate them.

Interestingly, the aggregate innovation rate initially decreases: the reason is that R&D is shifting upstream towards basic research, thereby reducing applied R&D; this slows down the completion of existing basic research projects, which has a negative effect on innovation. However, in the longer run, the increase in the flow of basic research results will more than compensate a thinner applied R&D effort.

It is interesting to observe an initial slump in innovation follows the beneficial increase in IPR, which may resemble the puzzling "productivity slowdown" measured in the US during the early Eighties[22]. Our stylized representation suggest that economists should not lose their optimism about innovation enhancing policies based on shorter term R&D reallocation effects coupled with improvements in the population educational choices. Notice that this explanation of the productivity slowdown complements the observation of GDP decrease associated to the mere reduction in manufacturing production $x(t)$, which is a consequence of the reduction in available inputs (skilled labour) and therefore not accounted for by the Solow residual.

Figure 19 assumes that the initial value of $\bar{\beta}$ was 0.55 and it suddenly changes to 0.65. Such a change will be detrimental to long term growth, because the basic research patent owner gets entitled to too large a share of the final invention value. This discourages applied R&D too much, which more than offsets the increase in basic research. Therefore the demand for skilled labour will fall and so will the skill premium and education.

[22] Of course, other important explanations, based on ICT or on adjustment costs, are not contradicted by our analysis.

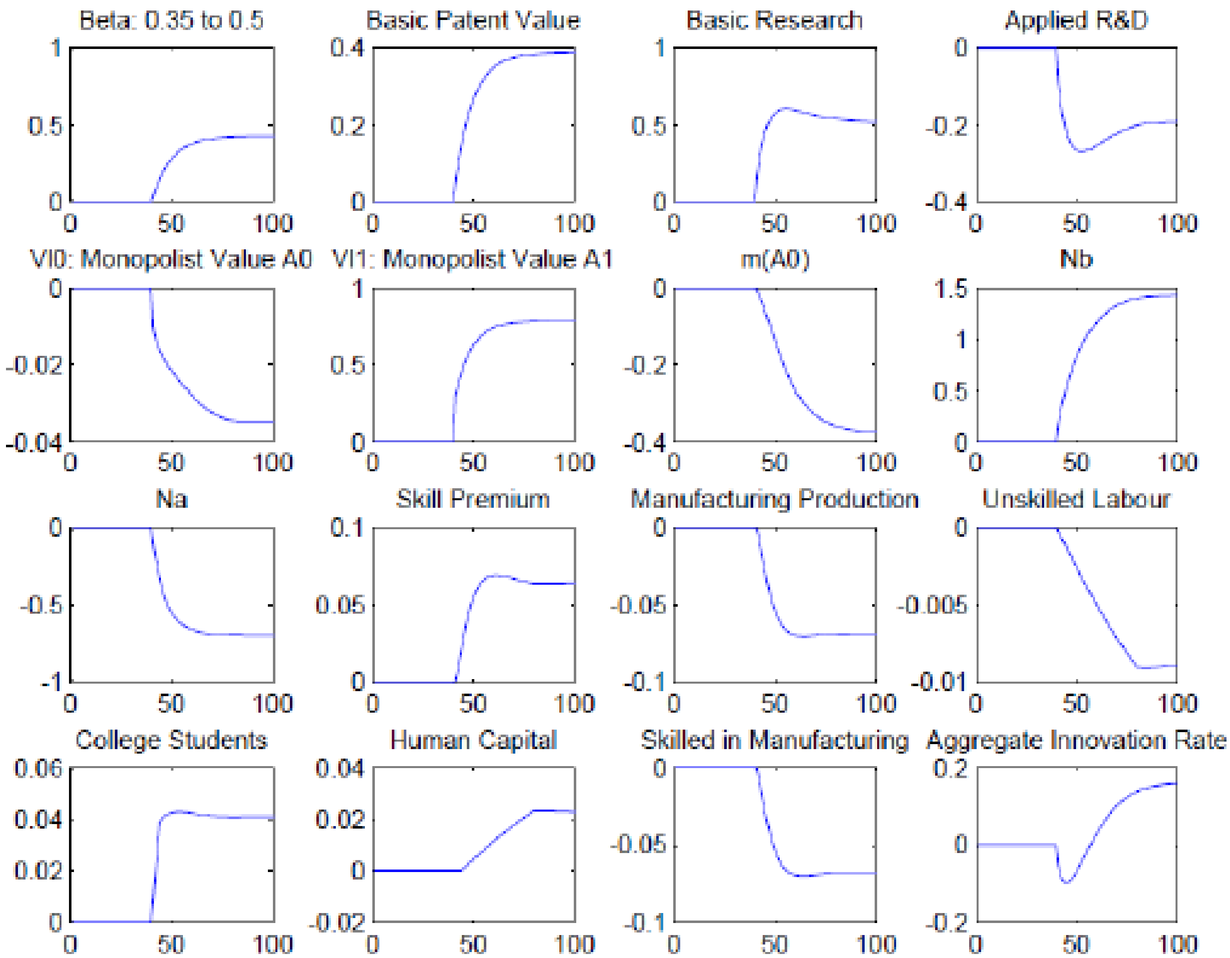

Figure 18: After 40 periods the initial value of β=0.35 suddenly changes to β=0.5.

The trajectories of the deviations of the value of each variable from its initial steady state value, divided by its initial steady state value.

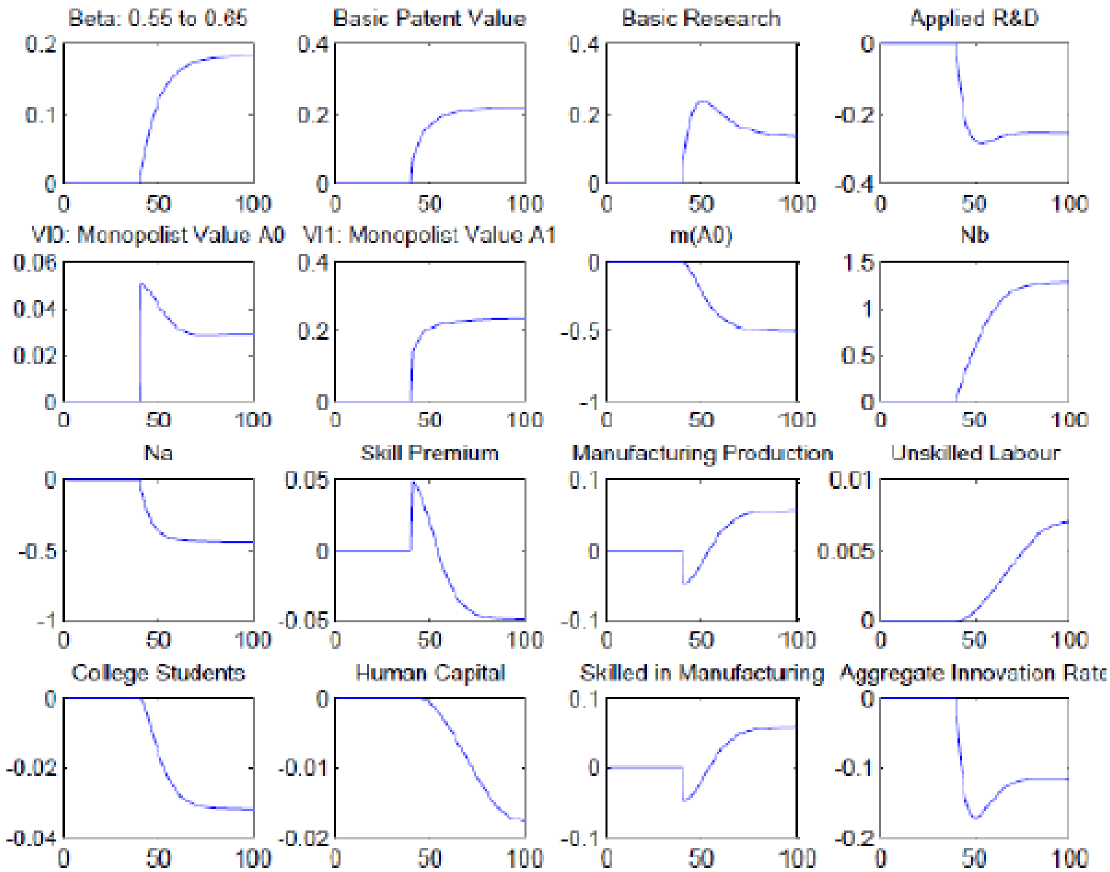

Figure 19: After 40 periods the initial value of β=0.55 suddenly changes to β=0.65.

The trajectories of the deviations of the value of each variable from its initial steady state value, divided by its initial steady state value.

Interestingly, the short term reactions of the skill premium and of manufacturing production could inspire wrong interpretations of the true long term effect of normative changes. In fact, as in the previous discussion, upon impact all stock variables are given, and mainly short term announcement effects prevail. Most notably, the expected gradual increase in $\beta(t)$ fails to penalize current applied R&D in the order of magnitude as it favours current basic research: basic R&D will be entitled of a larger share of the results of *future* applied R&D, not those of current applied R&D. Such temporary win-win situation boosts aggregate R&D labour and therefore raises the skill premium. However, as $\dot{\beta}(t)$ sets in, the temporary relief for applied R&D disappears, and its smaller share of the final product patent penalizes it so much that the ensuing drop in R&D employment outweighs the increase in basic research employment - the whole effect being corroborated by the gradual increase in $1 - m(A_0(t))$ - dragging the skill premium below the initial steady state level and therefore leading towards the new steady state, characterized by less R&D employment and less innovation.

Let the author that the simulations cast doubt on empirical evaluations of narrowing IPR policies based on relatively short term effects. The short term effects of a harmful tightening of upstream IPR look misleadingly similar to those of a beneficial bargaining power transfer towards basic researcher institutions.

The figures shown in this chapter are considerably robust and representative of the pro-upstream IPR changes mentioned so far: changing parameters returns very similar patterns of short, medium and long run dynamics.

5.7 Conclusions

This chapter has shown that the gradual evolution characterising the common law system implies gradual dynamics of the allocation of R&D, human capital, innovation and wage inequality. In light of well-known evidence of the steady increase in the skill premium and in education occurred during the Eighties and Nineties in the US, which set the basis for the innovative boom, the simulations presented here suggest that the driving force could have consisted in a beneficial gradual change of the court orientation, in favour of more protection of previously under-protected early stage innovators. On the other hand, should at some point early stage innovators become too protected, opposite trends could appear, as illustrated in Figure 19.

Since the common law system implies gradual change to new IPR regimes, the whole transitional dynamics has been analysed. The transition to a stricter regime does not always appear to be monotonic. This shows how assessments based on short term data could be misleading. For example, beneficial restrictions in IPR may result in a temporary reduction in innovation, which may seem a bizarre productivity slowdown.

5.8 Appendix

Proof of Proposition 1. From equation (5.33) and (5.6) follows that the steady state level of human capital per-capita is an increasing function of the skilled premium w_H, which we can write as $\overline{h}(w_H)$.

Plugging equation (5.17) into the skilled labour market clearing condition (5.16) yield:

$$\left[m(A_0) + (1 - m(A_0)) \left(\frac{\lambda_1}{\lambda_0}\frac{1-\beta}{\beta}\right)^{\frac{1}{a}}\right] n_B = \overline{h}(w_H) - x(w_H) \equiv \Psi(w_H) \tag{5.21}$$

with $\Psi'(w_H) > 0$. Inserting equation (5.19) into (5.21) we obtain:

$$\frac{n_B}{\beta\left[1 + \left(\frac{\lambda_0}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{\beta}{1-\beta}\right)^{\frac{1-a}{a}}\right]} = \overline{h}(w_H) - x(w_H) \equiv \Psi(w_H) \tag{5.22}$$

Plugging equation (5.18) into equation (5.14a) and (5.14e) we obtain:

$$w_H = \lambda_0 n_B^{-a} \beta v_L^0 = \lambda_0 n_B^{-a} \beta \left[\left(\frac{\lambda_1}{\lambda_0}\right)^{\frac{1}{a}}\left(\frac{1-\beta}{\beta}\right)^{\frac{1-a}{a}} + 1\right] v_L^1 \tag{5.23a}$$

$$\pi = \lambda_1 n_A^{1-a} v_L^1 = \lambda_1 \left(\frac{\lambda_1}{\lambda_0}\frac{1-\beta}{\beta}\right)^{\frac{1-a}{a}} n_B^{1-a} v_L^1 \tag{5.23b}$$

From the definition of profits and the steady state mass of unskilled labour, we know that $\pi = \pi(w_H)$, with $\pi'(w_H) < 0$. Dividing the last two equations side by side implies:

$$n_B \frac{1}{\beta\left[1 + \left(\frac{\lambda_0}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{\beta}{1-\beta}\right)^{\frac{1-a}{a}}\right]} = \frac{\pi(w_H)}{w_H}. \tag{5.24}$$

Plugging (5.24) into (5.22) gives:

$$1 = \Psi(w_H)\frac{w_H}{\pi(w_H)} \equiv \Phi(w_H) \tag{5.25}$$

where $\Phi'(w_H) > 0$. Therefore there exists a unique steady state level of the skill premium obtained as the solution to equation. (5.25). It is important to notice that, in this example, the steady state skill premium is independent of β.

The steady state innovation rate can be rewritten, after using (5.24), as:

$$\lambda_0 n_B^{1-a} m(A_0) = \frac{\left[\frac{\pi(w_H)}{w_H}\right]^{1-a}\beta^{1-a}}{\left[1+\left(\frac{\lambda_0}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{\beta}{1-\beta}\right)^{\frac{1-a}{a}}\right]^a} = \tag{5.26}$$

$$= \frac{\left[\frac{\pi(w_H)}{w_H}\right]^{1-a}}{\left[\left(\frac{1}{\lambda_0}\right)^{\frac{1}{a}}\left(\frac{1}{\beta}\right)^{\frac{1-a}{a}}+\left(\frac{1}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{1}{1-\beta}\right)^{\frac{1-a}{a}}\right]^a} \tag{5.27}$$

The numerator does not change with β as previously proved. The innovation rate is maximized when the denominator is minimized. Hence we need to find a value of β such that $\left(\frac{1}{\lambda_0}\right)^{\frac{1}{a}}\left(\frac{1}{\beta}\right)^{\frac{1-a}{a}}+\left(\frac{1}{\lambda_1}\right)^{\frac{1}{a}}\left(\frac{1}{1-\beta}\right)^{\frac{1-a}{a}}$ is minimized, which implies expression (5.20).QED.

5.8.1 Labour Supply and Education Dynamics

Unskilled Labour Supply

As previously shown, individuals born at t with ability $\theta(t) \in [0, \theta_0(t)]$ optimally choose not to educate themselves, thereby immediately joining the unskilled labour force. Hence a fraction $\theta_0(t)$ of cohort t remains unskilled their whole life. Summing up over all the older unskilled who are still alive - hence born in the time interval $[t-D, t]$ - we obtain the total stock of unskilled labour as of time t:

$$M(t) = \int_{t-D}^{t} \tilde{\beta} N(s) \theta_0(s) ds = \tilde{\beta} \int_{t-D}^{t} e^{gs} \theta_0(s) ds$$

where $\tilde{\beta}$ is the birth rate, $N(s)$ is the population at time s.

To stationarize variables, we divide by current (time t) population e^{gs}, obtaining:

$$m(t) \equiv \frac{M(t)}{N(t)} = \tilde{\beta} \int_{t-D}^{t} e^{g(s-t)} \theta_0(s) ds.$$

Its steady state level is:

$$m = \tilde{\beta} \frac{1 - e^{g(-D)}}{g} \theta_0 = \theta_0.$$

The change in the stock of the population-adjusted stock of unskilled labour is obtained by differentiating $m(t)$ with respect to time:

$$\dot{m}(t) = \tilde{\beta} \theta_0(t) - \tilde{\beta} e^{-gD} \theta_0(t - D) - gm(t) \tag{5.28}$$

As in Boucekkine et al. (2002) and Boucekkine et al. (2007) we obtain a crucial role for delayed differential equations.

College Population

The individuals born in t with ability $\theta(t) \in [\theta_0(t), 1]$ optimally choose to educate themselves, thereby becoming college students for a training period of duration Tr. Hence summing up over all the previous cohorts who are still in college - hence born in the time interval $[t - Tr, t]$ - we obtain the total stock of college population as of time t:

$$\widetilde{C}(t) = \tilde{\beta} \int_{t-Tr}^{t} N(s)(1 - \theta_0(s))ds = \tilde{\beta} \int_{t-Tr}^{t} e^{gs}(1 - \theta_0(s))ds.$$

In per-capita terms:

$$\widetilde{c}(t) \equiv \frac{\widetilde{C}(t)}{N(t)} = \tilde{\beta} \int_{t-Tr}^{t} \frac{N(s)}{N(t)}(1 - \theta_0(s))ds = \tilde{\beta} \int_{t-Tr}^{t} e^{g(s-t)}(1 - \theta_0(s))ds. \tag{5.29}$$

In a steady state:

$$\widetilde{c} = \tilde{\beta} \frac{1 - e^{g(-Tr)}}{g}(1 - \theta_0). \tag{5.30}$$

Taking the derivative of equation. (5.29) with respect to time we obtain:

$$\dot{\widetilde{c}}(t) = \tilde{\beta}\,(1 - \theta_0(t)) - \tilde{\beta} e^{-gTr}\,(1 - \theta_0(t - D)) - g\widetilde{c}(t). \tag{5.31}$$

Human Capital

The stock of skilled workers will coincide with those students who have completed their education and are still alive, born in $[t - D, t - Tr]$:

$$\widetilde{H}(t) = \tilde{\beta} \int_{t-D}^{t-Tr} N(s)(1 - \theta_0(s))ds = \tilde{\beta} N(t) \int_{t-D}^{t-Tr} e^{g(s-t)}(1 - \theta_0(s))ds \tag{3}$$

The total workforce (including students) in equilibrium equals total population, hence:

$$M(t) + \widetilde{H}(t) + C(t) = e^{gt}.$$

Due to heterogeneous learning abilities, in order to obtain the aggregate skilled labour supply, we need to multiply each skilled worker by the average amount of human capital that she can supply, given by the average skill of her cohort net of dispersion parameter Γ:

$$\int_{\theta_0(t)}^{1} (\theta - \Gamma) \frac{1}{1-\theta_0(t)} d\theta = \frac{1+\theta_0(t) - 2\Gamma}{2}.$$

Therefore the aggregate amount of skilled labour in efficiency units (skilled labor supply) is:

$$H(t) = \tilde{\beta} N(t) \int_{t-D}^{t-Tr} \frac{e^{g(s-t)}(1-\theta_0(s))\left(1+\theta_0(s) - 2\Gamma\right)}{2} ds$$

Dividing by time t population, we can express per-capita human capital as:

$$h(t) \equiv \frac{H(t)}{N(t)} = \frac{\tilde{\beta}}{2} \int_{t-D}^{t-Tr} e^{g(s-t)}(1-\theta_0(s))\left(1+\theta_0(s) - 2\Gamma\right) ds. \tag{5.32}$$

The steady state value is:

$$h = \tilde{\beta} \frac{\left[e^{g(-Tr)} - e^{g(-D)}\right](1-\theta_0)(1+\theta_0 - 2\Gamma)}{2g} \tag{5.33}$$

The dynamics of human capital can be studied by differenciating this expression with respect to time:

$$\begin{aligned} \dot{h}(t) &= -gh(t) + \frac{\tilde{\beta}}{2} e^{-gTr}(1-\theta_0(t-Tr))\left(1+\theta_0(t-Tr) - 2\Gamma\right) - \\ &\quad + \frac{\tilde{\beta}}{2} e^{-gD}(1-\theta_0(t-D))\left(1+\theta_0(t-D) - 2\Gamma\right). \end{aligned} \tag{5.34}$$

5.8.2 Transitional Properties of Educational Choice

The study of the transition dynamics of this model is complicated by the skilled/unskilled labour dynamics and by the endogenous population choice under perfect foresight. Key to the solution is the transformation of the integral equation for the ability threshold level for education into a set of differential equations.

Defining the present value of the unskilled wage incomes as $W_U(t) = \int_t^{t+D} e^{-\int_t^s i(\tau)d\tau} ds$ and the present value of the skilled wage income as $W_S(t) = \int_{t+Tr}^{t+D} e^{-\int_t^s i(\tau)d\tau} w_H(s)ds$, we know from (5.5) that

$$\theta_0(t) = \Gamma + \frac{W_U(t)}{W_S(t)}. \tag{5.35}$$

Defining

$$\begin{aligned} R_1(t) &= e^{-\int_t^{t+D} i(\tau)d\tau}, \text{ and} && (5.36) \\ R_2(t) &= e^{-\int_t^{t+Tr} i(\tau)d\tau} && (5.37) \end{aligned}$$

we can write:

$$\begin{aligned} \dot{W}_U(t) &= R_1(t) - 1 + i(t)W_U(t) && (5.38) \\ \dot{W}_S(t) &= R_1(t)w_H(t+D) - R_2(t)w_H(t+Tr) + i(t)W_S(t). && (5.39) \end{aligned}$$

Differentiating equations (5.36)-(5.37) with respect to time we obtain:

$$\begin{aligned} \dot{R}_1(t) &= R_1(t)(i(t) - i(t+D)), \text{ and} && (5.40) \\ \dot{R}_2(t) &= R_2(t)(i(t) - i(t+Tr)). && (5.41) \end{aligned}$$

These equations allow us to cast our model in a framework that can be studied in terms of delayed differential equations.

5.8.3 Expenditure and Manufacturing Dynamics

From equations (5.11) follows:

$$\frac{\gamma - 1}{\gamma} E(t) = (\gamma - 1) \frac{1}{1 - \alpha} m(t). \tag{5.42}$$

Log-differentiating with respect to time, using Euler equation (5.3) and the unskilled law of motion (5.28) yield:

$$i(t) - (\rho + g) = \frac{\dot{E}(t)}{E(t)} = \frac{\dot{m}(t)}{m(t)} = \frac{\tilde{\beta}\theta_0(t) - \tilde{\beta} e^{-gD} \theta_0(t - D)}{m(t)} - g \tag{5.43}$$

that - since $r(t) = i(t) - g$ - can be rewritten as

$$r(t) - \rho = \frac{\tilde{\beta}\theta_0(t) - \tilde{\beta} e^{-gD} \theta_0(t - D)}{m(t)} - g, \tag{5.44}$$

In the steady state: $r(t) = \rho$.

Chapter 6

Competition and Productivity Growth: a Schumpeterian Approach

6.1 Introduction

So far this thesis has considered innovation in the form of better products introduction, i.e. vertical product innovation. In this final chapter, process innovation is introduced to explore from a Schumpeterian growth perspective the link between competition and innovation had been largely explored within the industrial organization literature. In particular, the concept that market power provides the innovators with the reward for their research effort, and thus constitutes an incentive for any innovative activity, has been also examined extensively (Dasgupta and Stiglitz, 1980; Dixit and Stiglitz, 1977; Grossman and Helpman, 1991a and 1991b; Aghion and Howitt, 1992; Caballero and Jaffe, 1993).

A large theoretical and empirical literature has focussed on competition as a determinant of productivity growth. In the spirit of Joseph Schumpeter's (1942) trade-off between static and dynamic efficiency, the link between market power and growth has been embedded into the modern Schumpeterian debate since its earlier contributions (see Romer, 1990; Grossman and Helpman, 1991a and 1991 b; Aghion and Howitt, 1992;

Aghion *et al.,* 2005; see also Aghion and Griffith, 2005 for a recent survey). A large and growing body of recent analyses have focussed on industry level evidence to try to establish whether competitive pressure can act as an engine of innovation (Nicoletti and Scarpetta, 2003; Griffith et al 2006). Using data on regulation in many OECD countries, Alesina et al. (2005) find clear evidence that entry barriers in different sectors act as a deterrent for investment in those sectors.

The thesis that innovation should decline with competition was also tested empirically: most contributions seemed to invalid it by pointing out a positive correlation between competition and innovation (Geroski, 1995; Nickell, 1996). Boone (2000) explores the impact of competitive pressure on a firm's incentives to invest in product and process innovations. He presents a model with heterogeneous firms where the effects of competition on a firm's innovations depend on whether the firm is complacent, eager, struggling, or faint, and the trade-off between product and process innovations at the industry level emerges as a consequence of a rising competitive pressure.

Recent empirical evidence suggests that deregulation has a positive effect on growth in sectors (or countries) that are closer to the technological frontier, while this positive effect tend to disappear for more backward sectors or countries (see Aghion *et al.* 2006).

This chapter presents a simple model inspired by Lucas (1990) and where the provision of essential services (intermediate inputs, for example financial services or transports) for the production of the final good is characterized by a non-competitive market structure. The model also incorporates the framework developed by the recent recast of the endogenous growth presented in Aghion and Howitt's (2009) book (chapter 4). The ultimate purpose is to show how the lack of competition in an intermediate essential sector, like the service sector, is actually able to prevent productivity increase in the final sector. A large empirical literature documented how the presence of regulatory barriers in non-manufacturing sectors is detrimental for the economic performance in many countries. Barone and Cingano (2011) consider the effect of the upstream service regulation in downstream service-intensive manufacturing industries. They find that relaxing regulation (in the form of barriers to entry or restrictions on prices or fees) in service industries (like professional services, utility providers, or financial services) has a non-negligible positive impact on the value added, productivity, and export growth of intensive service utilizers. In line with this approach, pioneered for the financial services by Rajan and Zingales (1998), the model presented in this chapter examines the effects of the presence of monopolies in the service sectors on the manufacturing sectors which use these services as inputs for their production.

The rest of the chapter is organized as follows. Section 6.2 sets up the model. Section 6.3 describe the detail of the innovation process and derives the policy implications. Section 6.4 sets up the aggregate properties of the economy and computes the aggregate growth rate for the final output. Finally, section 6.5 concludes.

6.2 The Model

This section describes a model with imperfect competition in intermediate service markets in a modified version of the basic multisector Schumpeterian model of Aghion and Howitt (2009, chapter 4).

Consider an economy composed of a mass L of identical one-period-living individuals. Assume that, at every time $t = 1, 2, ..$, these individuals only care about consumption c_t, their instantaneous utility function being $u(c_t) = c_t$. Each individual is endowed with one unit of labour, which she supplies inelastically.

In this economy, the final output is produced with a technology represented by a Dixit-Stiglitx production function, with perfectly competitive firms combining labour and a continuum of intermediate services:

$$Y_t = L^{\alpha} \int_0^1 A_{it}^{\alpha} S_{it}^{1-\alpha} di \tag{6.1}$$

where Y_t is the final output produced in the economy at time t; L is the economy labour supply; S_{it} is the quantity of the service $i \in [0,1]$ used in the production of the final good. The productivity coefficient A_{it}^{α} is the TFP characterizing the sector i at time t; $\alpha \in (0,1)$.

The economy is made up of three sectors: a final good sector (competitive), a continuum intermediate service sectors (monopolistic), and a continuum of R&D sectors (monopolistic). The final output Y_t is used for consumption, investment, intermediate service production, and R&D.

Each intermediate service producer $i \in [0,1]$ has its own monopoly, and sells the service at a price which reflects its marginal productivity on the final sector, obtained from equation (6.1) as:

$$p_{S_i t} = \frac{\partial Y_t}{\partial S_{it}} = (1-\alpha)\left(\frac{A_{it}L}{S_{it}}\right)^{\alpha}. \tag{6.2}$$

Similarly, the wage rate w must equalize the marginal product of labour in the final sector, which is again derived by differentiating equation (6.1) respect to L:

$$w = \frac{\partial Y_t}{\partial L} = \alpha L^{\alpha-1}\int_0^1 A_{it}^{\alpha} S_{it}^{1-\alpha} di. \tag{6.3}$$

Each monopolist seeks to maximize its profit taking the demand function from the final sector, equation (6.2), as given:

$$\max_{S_i} \Pi_{tS_i} = \max_{S_i} p_{S_i t} S_{it} - bS_{it} = \max_{S_i} (1-\alpha)\left(A_{it}L_t\right)^{\alpha} S_{it}^{1-\alpha} - bS_{it},$$

where b denotes the unit cost for the service production.

The first-order condition for the maximization problem is:

$$(1-\alpha)^2 \left(A_{it}L\right)^{\alpha} S_{it}^{-\alpha} - b = 0$$

from which follows the equilibrium quantity of the intermediate service provided in the industry i:

$$S_{Mit} = A_{it}L\left[\frac{(1-\alpha)^2}{b}\right]^{\frac{1}{\alpha}}. \tag{6.4}$$

By substituting equation (6.4) into equation (6.2), one can get the price of the intermediate service as a function of the unit cost:

$$p_{MS_it} = \frac{b}{1-\alpha}. \tag{6.5}$$

Hence, being the monopolistic price p_{MS_it} higher than the unit cost $((1-\alpha) \in (0,1))$, the quantity of the intermediate service provided to the innovative final sector is actually lower than the quantity that would be offered had the market been perfectly competitive, with marginal cost pricing $p_{S_it} = b$. Plugging $p_{S_it} = b$ into equation (6.2), gives competitive supply $S_{Cit} = A_{it}L\left[\frac{(1-\alpha)}{b}\right]^{\frac{1}{\alpha}} > S_{Mit}, \forall\alpha \in (0,1)$.

6.3 Process Innovation

The result of the activity of each R&D sector is increasing the TFP and the output in the final good sector. More specifically, in each period and in each sector, an individual is randomly selected to get an opportunity to produce a probability of innovation $\mu \in [0,1]$, by sustaining a R&D cost, in terms of the final good, represented by quadratic function $\frac{\mu^2}{2}A_{it}$, where A_{it} reflects the increasing difficulty in advancing more sophisticated technologies. By paying the R&D cost, the individual can attempt an innovation. If successful, the innovation will create a more effective process for producing the final output using service i. Specifically, the single-factor TFP of the service i will go form the current period value A_{it} up to γA_{it}, where $\gamma > 1$.

If the potential innovator (i.e. the individual selected to attempt an innovation) in a sector i is successful, she will gain a perfectly enforceable patent on the new use of service i in that period. Thus the reward for the successful innovator is represented by the increased final good production, here denoted Δ_{it}, that she will eventually appropriate.

Since the potential innovator succeeds with probability μ, the expected revenue is given by $\mu\Delta_{it}$, while, independently from her succeeding, the cost of the R&D activity is given by $\frac{\mu^2}{2}A_{it}$.

Following an innovation in service industry i in period t, the patent holder is able to extract the whole surplus of the buyers - i.e. the final good producers - by setting the price for the newly introduced production technique as $p_{A_{it}} = \Delta_{it}$. For such a price the final good producers are indifferent between buying the technology from the monopolist or adopting the technique which is available at lower price, hence they end up with buying the new technique from the monopolist.

By substituting equation (6.4) into the final good production function, equation (6.1), yields the value of the final output:

$$Y_t = L^\alpha \int_0^1 A_{it}^\alpha \left\{ A_{it} L \left[\frac{(1-\alpha)^2}{b} \right] \right\}^{\frac{1-\alpha}{\alpha}} di, \tag{6.6}$$

which, after some simple algebra becomes:

$$Y_t = \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}} L \int_0^1 A_{it} di. \tag{6.7}$$

The increase in the value of the final production bore by the difference in the productivity in the service industry i where innovation has occurred is given by:

$$\Delta_{it} = \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}} L\gamma A_{it} - \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}} L A_{it} = \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}} L(\gamma - 1) A_{it}$$

Hence, in every service industry, ex ante, the individual selected to attempt an innovation faces the following expected profit maximization problem:

$$\max_\mu \mu (\gamma - 1) A_{it} L \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}} - \frac{\mu^2}{2} A_{it}. \tag{6.8}$$

which implies the following first order condition:

$$(\gamma - 1) A_{it} L \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}} - \mu A_{it} = 0 \tag{6.9}$$

From equation (6.9) it easy to verify that the following **Lemma 2** holds.

Lemma 2 *The innovation arrival rate occurring with a non-competitive intermediate service, $\mu_{MS_i} = \mu_{MS}$, is lower than the innovation arrival rate associated with a perfectly competitive service sector, $\mu_{CS_i} = \mu_{CS}$.*

Proof. *The first order condition for a maximum in the perspective innovator's expected profit maximization problem (6.9) implies:*

$$\mu_{MS_i} = (\gamma - 1) L \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}} \equiv \mu_{MS}$$

and

$$\mu_{CS_i} = (\gamma - 1) L \left[\frac{(1-\alpha)}{b} \right]^{\frac{1-\alpha}{\alpha}} \equiv \mu_{CS}.$$

Therefore the statement follows, with $\mu_{MS} < \mu_{CS}$, $\forall \alpha \in (0,1)$. ■

6.4 Growth

The aggregate properties of the economy depend on the aggregate productivity parameter $A_t = \int_0^1 A_{it} di$,

which, plugged into equation (6.7)) gives:

$$Y_t = A_t L \left[\frac{(1-\alpha)^2}{b} \right]^{\frac{1-\alpha}{\alpha}}. \tag{6.10}$$

The economy's GDP equals the output of the final good Y_t minus the amount used to produce each intermediate service:

$$GDP_t = Y_t - \int_0^1 bS_{it}di. \quad (6.11)$$

Using equation (6.4) to substitute for each S_{it} into this integral and combining it with equations (6.10) and (6.11) yields:

$$GDP_t = A_t L\tilde{\alpha}$$

where the composite parameter $\tilde{\alpha} = \left[\frac{(1-\alpha)^2}{b}\right]^{\frac{1-\alpha}{\alpha}} - b\left[\frac{(1-\alpha)^2}{b}\right]^{\frac{1}{\alpha}}$. The economy's GDP its proportional to its effective labor supply. It is worthwhile to notice that, since $(1-\alpha)^2 < (1-\alpha)$, the barriers to competition in the service sectors reduce the level of per-capita GDP. Since the focus of this chapter is on the growth effects, we move on to the growth rate analysis.

Since per capita GDP, $A_t\tilde{\alpha}$, is proportional to the aggregate productivity parameter A_t, the economy's growth rate g_t is proportional to the growth rate of A_t:

$$g_t = \frac{A_{t+1} - A_t}{A_t}. \quad (6.12)$$

In each industry i, with independent probability μ an individual will innovate, resulting $g_{it} = \frac{\gamma A_{it} - A_{it}}{A_{it}} = \gamma - 1$; and with probability $1-\mu$ the individual will fail to innovate, resulting in $g_{it} = \frac{A_{it} - A_{it}}{A_{it}} = 0$. Hence, good luck in some sectors will be offset by bad luck in other sectors:

$$A_{it} = \begin{cases} \gamma A_{it} & \text{with probability } \mu \\ A_{it} & \text{with probability } 1-\mu \end{cases}.$$

By the law of large numbers, the fraction of sectors that innovate in each period will be μ. Therefore the economy-wide TFP parameter A_t can be expressed as μ times the average TFP among sectors that innovated at time t, plus $(1-\mu)$ times the average TFP among sectors that did not innovate at time t:

$$A_{t+1} = \mu\gamma A_t + (1-\mu) A_t.$$

From equation (6.12) follows:

$$g_t = \mu(\gamma - 1). \tag{6.13}$$

Equation (6.13) expresses the growth rate of the economy as the frequency of innovations, μ, times the proportional increase in the TFP resulting from each innovation, $(\gamma - 1)$. Therefore, if the service industries are monopolized, the equilibrium growth rate will be $\mu_{MS}(\gamma - 1)$, strictly lower that the growth rate $\mu_{CS}(\gamma - 1)$, which would prevail if the services were open to perfect competition.

6.5 Conclusions

The model presented throughout this chapter stressed out a possible mechanism through which non-competitive intermediate markets curb TFP growth in the final sectors. Unlike more sophisticated models (like, for example Bourlès et al. 2010), here the unique channel through which the lack of competition in the intermediate sectors can restrain productivity growth in the final sectors is the limited provision of the essential services occurring just because of the limited competition (monopoly in the extreme case examined here).

Nevertheless, the very simple structure adopted allowed the model to clearly highlight a mechanism through which the non-competitive market structure in the intermediate service sectors directly negatively affects the innovation arrival rate of the economy. The structure adopted here also allowed examining the effects on the economy of presence of two different monopolized tasks: the intermediate service provision and the use of the innovation. The second is conceived as non-competitive for the newly introduced more productive processes complementary to the intermediate services are immediately protected by patents. On the contrary, the service providers operate in a non-competitive environment only because of the regulation of the market, in the form of unspecified barriers to entry. Given the widely documented relevance of such sectors for the developed economies (professional services, utility providers, transports, financial services), it appears important to study the effects of such a regulation on the innovative capacity of the economy. Albeit the very simple structure adopted, the model presented throughout this chapter captured the effect of both sources of monopoly power: the patents resulting from the R&D activity, positively affecting the heterogeneous productivities of the different segments of the final good production technology (by increasing the TFP attached to each intermediate service), and the barrier to the competitive entry in the provision of services determined by the market regulation detrimental to industry innovation and macroeconomic growth.

Chapter 7

Final Conclusions

My thesis investigated endogenous growth theory and institutional aspects of growth enhancing policies. In particular, within a dynamic general equilibrium model, I tried to show how changes in the patent law, in the system of innovation incentives, and in the court orientation (with a special reference to common law systems) may affect the long term performance of the economy – with special attention to innovation, functional inequality, and education.

The importance of integrating the traditional microeconomic approach to the economics of innovation with the general equilibrium approach appeared in fact more and more evident in the purpose of examining the effects of different policies on market and non-market oriented institutions in the innovation process. In this sense, here I tried to give microeconomic foundation to the channels through which the system of innovation incentives operates in generating better or worse performances in terms of both basic and applied research at the macroeconomic level.

Since the 80's, the patent system in the US has undergone substantial changes resulting in an increase in the patent protection granted to the first inventors In other words, patent holders became better protect their inventions against imitation as well as *subsequent innovation*. In an environment with sequential innovation, these overlapping patent rights across sequential innovators lead to contrasting effects on the incentives for

R&D. On one hand, the traditional view suggests that stronger patent rights improve the protection for existing inventions and hence increase its value to the patent holders. On the other hand, the recent argument against patent protection suggests that stronger patent rights stifle innovation by conferring too much power onto existing patent holders, who use this power to extract surplus from subsequent innovators rather than providing more innovation[1]. In this thesis, I developed a growth model to shed some light on this current debate on whether patent protection stimulates or stifles innovation. In particular, Chapter 1 introduced the reader to the R&D-based growth theories and provides an explanation of the early attempts and of the main successful approaches followed by this literature to envisage a way for modelling the human inventive activity into an economic growth model. Throughout the chapter, emphasis has been placed on the difference between horizontal and vertical innovation processes: the horizontal innovation process consists of an ever expanding product variety which may be interpreted both as final goods and as intermediate inputs for the production of the final output, while the vertical innovation process is so defined because new ideas get incorporated into better-quality versions of the existing goods, in the form of either a new good which provides a higher quality service or in the form of a new production process for the same good. In this case growth is generated by a random sequence of quality improving innovations ("vertical") – resulting from uncertain research activities – on the existing goods which can be produced at a lower cost providing the same quality service of the actual vintage. Since the first generation of the Schumpetarian growth models was affected by the so called scale effect on the per-capita output growth rate (i.e. the per-capita output growth rate increases with the number of researchers in the economy), this chapter showed the main mechanism identified to remove the scale effect, namely the increasing difficulty in R&D, the dilution effect, and the updating cost productivity adjustment.

Chapter 2 developed an R&D-based growth model with basic and applied research to analyse the growth effects of the patentability of basic research. Since in 1980 the Bayh-

[1]See, for example, Bessen and Meurer (2008), Boldrin and Levine (2008) and Jaffe and Lerner (2004).

Dole Act granted the US universities the right to patent and license the results of federal government funded research, the patenting activity of non-for-profit research institutions has been steadily increasing in the US and the trade-off between providing the basic innovators with the right incentive and the need of non-restricting the access to basic knowledge has become one of the most debated in the dialogue between industry and academia. In a first scenario, only the public sector institutions undertake basic research, rendering all results publicly available for firms, racing to find patentable applications. In a second scenario basic research itself is privatized, and hence patented by private firms. I have estimated the unobservable research productivity parameters with the US data immediately preceding the major reorganization of university and basic research in the 80s, and used such estimates to simulate the two scenarios. The resulting simulations show that public R&D system, prevailing at that time, was indeed outperforming every privatized alternative scenario.

Chapter 3 calibrated a modified version of the same model to simulate the introduction of Kremer's (1998) mechanism for inducing innovation by means of auctions for new patents, run by the public sector in order to finance innovators and freely disseminate most of the new ideas. My work is the first attempt to use Kremer's idea to address the issue of the patentability of basic research and the financing of early innovation. It turns out that private research would have been enhanced if the government bought out the research tool patents and rendered them publicly available to the private applied R&D firms, as suggested by Michael Kremer (1998).The same Chapter 3 also studied quantitatively the impact of the so called "research exemption" of patented basic knowledge. Under the research exemption doctrine, if the second innovator is successful in developing a saleable product or process, then he or she can patent it and yet infringe another patent.

Chapter 4 tried to provide robustness to the results: the data largely confirm the results previously obtained with a different dataset: maintaining free access to basic research would have been better for innovation despite the assumed inefficiency of the public laboratories and universities in targeting the right sectors to devote their research efforts.

Chapter 5 analysed the macroeconomic effects of patent protection by incorporating a two-stage cumulative innovation structure into a quality-ladder growth model with skill acquisition. We considered three issues (a) the over-protection vs. the under-protection of intellectual property rights; (b) the evolution of jurisprudence shaping the bargaining power of the upstream innovators; and (c) the implications of strengthening patent protection on wage inequality and growth. It showed analytically and numerically how the jurisprudential changes in intellectual property rights witnessed in the US after 1980 can be related to the well-known changes in wage inequality and in education attainments. Basic research patents may have grown disproportionately due increasing jurisdictional protection, eventually compromising applied innovation, education, and growth. By simulations, it is showed that the dynamic general equilibrium interactions may mislead the econometric assessment of the temporary vs persistent effects IPR policy.

In the model economies presented throughout Chapters 2, 3, 4, and 5 of this dissertation, several market failures are present, in particular:

1. imperfect competition in the final good sectors;
2. external effects of R&D via the intertemporal spillovers;
3. external effects of basic R&D on applied R&D;
4. free entry into R&D patent races.

The first three market failures would suggest a less than optimal equilibrium amount of R&D, while the patent races would suggest too much R&D as a possible outcome. Moreover, since the composition of R&D between basic and applied research plays a major role in this framework, it is likely to expect that a social planner would prefer it to be as balanced as possible.

A formal social planner solution has not been attempted by this dissertation. However, the different welfare levels associated with the different institutional scenarios envisaged regarding the patentability of basic research results can be computed, and has been computed by the author, in several numerical simulations of the models presented. A general conclusion is that there is no specific welfare-maximizing institutional arrangement, because, depending on the parameters, the public basic research scenario - characterized by unpatentable basic research outputs - may or may not dominate the privatized basic research scenario. Hence, no general result would be emerging from a welfare analysis:depending on the values of the relevant parameters the welfare performance of the decentralised economy could be lower or higher than the first best. The most interesting result of my simulations is that the more difficult basic research relative to applied research the better the public basic research scenario; on the other hand, the more difficult applied research relative to basic research, the more desirable a privatized scenario, characterized by patentable basic research outputs.

Finally Chapter 6, explored a way of introducing an additional source of market power in the Schumpeterian model, beside the monopoly power conferred by patents. Specifically, we assumed that (as widely documented by the empirical literature) the provision of essential services (intermediate inputs, for example financial services or transports) for the production of the final good is characterized by a non-competitive market structure. The model showed how the lack of competition in an intermediate essential sector, like the service sector, is actually able to prevent productivity increase in the final sector.

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