Innovations and Tournaments in an Endogenous Growth Framework

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To Katerina
(for constant support and inspiration)

Abstract

In the context of a patent race, if innovation is sequential and there is no cross licensing, patents offer the patent owner monopoly control over his innovation, allowing him to block all relative future R&D. Against this background, this thesis shows that patent protection can foster innovation because it offers the innovator an incentive to innovate. However, the monopoly that the patent holder enjoys can lead him to rest on his laurels, reducing his innovative effort and, at the same time, force some innovators to abstain from innovating, reducing knowledge spillovers. The above can lead to a humped shaped relationship between patent protection and output growth.

Bearing the above in mind, this thesis further engages in showing that in economies with restricted innovative capabilities a central planner may find it optimal to offer limited patent protection compared to very innovative economies. In a similar fashion, a firm working on a new technological paradigm may find it optimal to allow competitors to free ride on its technology, in order to benefit from the extended knowledge spillovers that its competitors will generate.

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Writing a thesis is a rather demanding exercise, which requires both intellectual capacity and physical stamina. This becomes even more difficult when one is away from home. I thought that my active, and rather lengthy, military experience would have given me endurance to safely surpass all obstacles. It wasn't so. Without the help and endurance of my supervisor Nicholas Rau, this thesis may have only been just another uncompleted project, gathering dust on my desk. In the course of writing up of this thesis, Nicholas Rau was not my only help. A special note goes to David Ulph, for his espousal and his help in numerous occasions. Stephen Martin the editor of the International Journal of Industrial Organization deserves my gratitude for allowing me to publish my ideas. This would not have been possible without the help of John Beath, Al Link and John Scott. Their assistance in the shaping of chapter two is gratefully recognized.

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Introduction

This thesis pursues the study of innovation within the context of a patent race. Specifically, chapter one is a literature review. The aim of this chapter is to introduce the reader to the economics of intellectual property protection, with emphasis on patents. Bearing in mind that the economic arguments surrounding patents must be structured taking into consideration the current legal framework, chapter one pays special attention at how the legal environment may shape the incentives to innovate, both on the national and international level, by means of treaties such as the Paris convention and TRIPS. In addition, chapter one engages in clarifying any specialized terms that will henceforth find frequent use, such as the term patent breadth.

Chapter two, which is based on Panagopoulos (2003), contains a more I.O. based approach, compared to the macro modelling strategies that chapters three and four follow. In doing so, it concentrates on the question of optimal patent protection, the one that will maximize a firm's profits. In this chapter, profits depend on technology, while technology depends on knowledge spillovers. In addition, knowledge spillovers depend on the ability of innovators/firms to reach an exogenous set target that is set by society. A good example for such a target is the goal to create a better AIDS treatment. The more capable a firm is of reaching this target the more useful its technology will be in terms of knowledge spillovers to other firms working on similar research. Bearing the above in mind, in the context of a patent race in which many firms try to reach such an exogenously set target, a firm may find it optimal to allow competitors to free ride on its research, in the hope to benefit from enhanced knowledge spillovers that its competitors will collectively create. Such behavior is likely when the firm has developed a new technological paradigm that needs further development. This line of thinking can account for the historical evidence on the development of the transistor. It should be noted, that for the sake of simplifying the argument, this chapter concentrates on cooperative solutions only. All the remaining chapters will also follow this approach. This intuition is in turn used to explain the lack of research joint ventures (RJV) between universities and firms, noting that in the 1980s the US government took specific steps, in the form of an Act passed by the Congress (the Bayh-Dole Act) whose aim was to promote such ventures.

The argument introduced in chapter two suggests that firms who engage in research and development (R&D) on new technological paradigms (such as biotechnology, software and computer technology) are more likely to form an RJV with a university. The reason is that such firms optimally choose minimal intellectual property protection (lower profits), in effect sharing their innovation, so as to benefit from increased knowledge spillovers. Thereby, the opportunity cost of joining an RJV for firms (universities) working on mature (well developed) technologies is greater, making such partners unlikely candidates for RJVs. Empirical evidence offers support for such a result.

It should be noted that this chapter operates under the assumption that universities are not different from firms, both in the way they maximize profits, as well as in their research specialization. If one is to make the more realistic assumption, as in Beath *et al.* (2003), that universities specialize on new technological paradigms, then the results of this chapter are reinforced. Nonetheless, the question remains, how different are universities from firms in terms of their research? To this there is no definite answer. The Bayh Dole Act allowed universities to make greater use of their patents. This Act has resulted in an increase in university patenting and a change in the way universities view patents.[1] However, evidence from Henderson, Jaffe and Trajtenberg (1998) and Sampat, Mowery and Ziedonis (2003) indicate that there is no clear verdict out yet, on whether this Act has led to any significant changes on the quality of university research. On the other hand, there is a growing literature on technology incubators, science parks and university startups, showing that university research is closer to private research than before, and that this trend is likely to increase as time passes.[2]

Throughout this chapter, as well as in chapters 3 and 4, the results stem from a tournament where each innovator has an exogenously given probability of winning the tournament. This exogeneity is one of the main drawbacks of this thesis. Nevertheless, in the appendix of chapter four I will suggest a way to endogenise this probability. This appendix is structured around the assumptions of chapter four. However, it is straightforward to generalize this method and use it for chapters two and three. If one is to use this method, even though the results of the thesis remain the same, the mathematical functions become cumbersome and most results rest on graphical interpretations. Another drawback that is common to both chapters two and four, is the exogenous introduction of a function that determines the number of innovators who find it profitable to participate in the tournament. This function is important because it allows one to determine knowledge spillovers. Bear-

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[1] See Jensen, Thursby and Thursby (2003).

[2] See Siegel, Westhead and Wright (2003), Wright, Vohora and Lockett (2004), and Audretsch, Lehman, and Warning (2004).

ing the above in mind, chapter four introduces some intuition that is based on financial economics, which allows one to determine through a simulation the number of innovators who take part in the tournament.

Chapter three shifts the attention away from the patent protection that maximizes profits to concentrate on the one that maximizes production. Specifically, working under the assumption that two firms participate in a tournament, where only the winner will be able to embody his innovation into the final product, this chapter aims at finding the patent protection that will allow a central planner to maximize production. Innovation in this chapter is assumed to be a twofold process, which rests on prior art and risk taking experimentation, and it is up to the firm to find the optimal combination between the two. To provide a present day analogue of this twofold process, as suggested by John Beath, one can think of this relationship as describing the ability of the NHS to provide medical treatment. Specifically, the NHS employs, in broad terms, two categories of workers, medical staff (nurses and doctors) and researchers. Medical staff functions as prior art (in the sense that they encompass what we already know in treating diseases), while researchers present us with new and yet untested techniques that may lead to breakthroughs as well as pitfalls. Accounting for the above, one can think of this framework as one that deals with how to best split medical and research staff in such a way that will increase the NHSs ability to offer medical services.

The main argument of this chapter is that the monopoly that patents offer can lead the innovator to rest on his laurels, diminishing any incentives to innovate. There is a well known historic precedent that displays how lack of competition can lead an innovator to rest on his laurels. Specifically, in the 1890s Edison successfully patented his light-bulb filament invention; however, until the patent expired, General Electric did not improve this technology. In addition, even though other companies had created a better light bulb, General Electric managed (through successful litigation) to keep competitors out of the market, increasing its market share and sales.

Based on the above, chapter three shows that there is a positive relationship between patent strength and the ability of the firm (economy) to experiment/innovate. This implies that economies that have the ability to successfully experiment/innovate may find it optimal to have stronger patent protection compared to economies that are not capable of successfully doing so. Hence, on the international level, patent protection should not be uniform. Instead it should vary depending on the economy's ability to innovate. This line of thinking runs counter to the one-policy-fits-all argument propagated by the TRIPS agreement.

The last chapter revisits the main issues discussed in chapters two and three, introducing them in one unified, albeit simplified, endogenous growth framework. Specifically, while accounting for the view that patents reward the innovator, acting as stimuli, this chapter also concentrates on two additional ways through which stronger patent protection can affect innovation. The first one, as in chapter three, is based on the idea that the more one feels a competitor's breath behind his back the more he is forced to run. This idea, which goes back to Beath, Katsoulakos and Ulph (1989), as well as Harris and Vickers (1987), implies that a decrease in patent protection should increase competition for the most successful technology (as all innovators will be able to freely copy the latest innovation) forcing competitors on adopting risky innovation strategies. Such strategies can potentially lead to breakthroughs as well as failures.

The second way is examined by looking at knowledge spillovers, as in chapter two. Specifically, an increase in patent protection makes it harder for other innovators to by-pass a patent. Lerner (1995), working on biotechnology firms, finds that this difficulty may force some innovators to abstain from innovating in this particular sector. Such a reduction in innovative effort may lead to a drop in knowledge spillovers, negatively affecting innovation.

Similar to chapter three, chapter four will be based on a tournament, where many heterogeneous innovators participate, the winner of which will be the only innovator to use his technology in production. Technology in this framework will depend on knowledge spillovers, prior art, research workers and luck. Simulating the model, in order to derive the patent strength that maximizes output growth, a humped-shaped relationship between patent protection and output growth is derived. This shape accords with recent empirical findings by Lerner (2004).

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Chapter 1
Litterae Patentae an Age Old Institution in the Modern Era

1.1 Introduction

When Yale professor Daniel J. Kevles presented his report on the '*History of Patenting Life*' to the European Group of Ethics in Science and New Technologies,[3] he was in effect describing one of the newest chapters on intellectual property. At the center of his attention was the Chakrabarty case, involving the genetic modification of a pseudomonas bacterium. By all measures, this was one of the most important patent cases ever taken to the US Supreme Court, and its success opened the way to the controversial biotechnology patents. Undoubtedly, patents have evolved quite a long way from being simple *Litterae Patentae* (open letters), through which 17th century British monarchs would grand a reward, in the form of a monopoly, to innovators as well as to various forms of commercial endeavor, such as cotton mills. In our day they are not simple rewards, they are means that, with good usage, can lead to further innovation, as well as to problems that in many cases may have been unanticipated by law makers. The ethical issue created by life patents is a simple and popular example.

The aim of this chapter is to offer a review of the economics of patents. To this effect, I will offer a short historic account of the patent system, plus an introduction to the legal

[3] See Kevles (2002).

requirements and justifications of patent law. In addition, I will elaborate on the best ways to design a patent, and more importantly, I will provide statistics that aim at manifesting the degree of importance of patents during the last 20 years. It is the latter attribute of this review that mostly differentiates it from Gallini and Scotchmer (2001), and Gallini (2002), which revisit the question of whether patents are the best way to reward innovation.[4]

Since this chapter concentrates on the economics of patents, the legal, sociological and philosophical literature will only sporadically appear in the following pages. Furthermore, the managerial literature will not be accounted for at all. This literature mostly concentrates on prescribing remedies to practitioners on how to navigate the patent system best, and on how to improve on their business practices by using patents. Therefore, by reviewing it one will be shifting the center of attention from theory to practice and from patent design to business practice.

This chapter is structured in the following way: I begin by looking at the emergence of the international patent system, in section two. Then, the following section introduces a short discussion on alternative means of rewarding innovativeness. The focus of section four will be on the advantages and disadvantages of the patent system. The final subsection of section four will elaborate on patent litigation, which is considered by many to be a major malady in an otherwise well functioning system. Section five revisits a question that has been at the heart of academic debate in the last fifteen years, concerning the optimal design of patent system, to be finally followed by the conclusions.

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[4] For a literature review one could also look at Langinier and Moschini (2002).

1.2 A description of the patent system

The patent system is justified on the basis of providing incentives to innovation. However, providing motives for innovators is far from a modern concept. Incentives in various forms were practiced throughout the ancient world.[5] Nevertheless, it seems that protecting one's innovation from imitators was merely a matter of secrecy and tacit knowledge.[6] One first encounters the main characteristics of a patent system in the 13th century, when Germanic rulers in the Tyrolean region granted awards for mining discoveries, see Kaufer (1989). However, the credits for codifying the first patent law go to Venice, back in 1474, where the first patent law was codified. In later years this code was to form the basis for both the French and the British patent systems.[7]

In modern times patents are issued by patent offices, which examine a set of legal requirements such as novelty, non-obviousness and industrial applicability (in Europe), as well as usefulness (in the USA). If one is to look at a patent application, it has two main parts. The first one is a specification of the invention. This part is written like a science article describing the problem and the steps taken to solve it. The second part consists of a set of claims. These claims define what the innovator considers to be the breadth of the invention, the technological territory claimed for control through the right to sue for infringement.

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[5] To offer a well-cited example, the Archimedean buoyancy principle (the one that caused Archimedes's legendary Eureka phrase) was motivated by an award offered by the Governor of Syracuse.

[6] In many cases innovators did not seek protection at all. Many famous discoveries, such as the Pythagorean principle and the Archimedean buoyancy principle fall under this category.

[7] For a complete historic account of the patent system from the middle ages to present, see Epstein, Laurie and Elder (1992) and Wegner (1993).

However, even today national laws and courts' jurisprudence vary considerably in the way they treat patents. This difference is further exaggerated in the treatment that foreign patents frequently receive. Such changes have created a need for harmonization of different patent systems and practices. This need first became apparent in the late 19th century and was to increase further in the 20th century, because more and more innovations found transnational applications, creating the need to protect foreign innovators.

Aiming to accommodate this need, the Paris convention was signed in 1883. It provided that each of the signatory countries would treat domestic and international patentees equally. The next major step was taken in 1984, under the auspices of the World Intellectual Property Organization (WIPO). This agreement, which came into being in 1990, introduced a centralized patent procedure.[8] WIPO was but a small step to patent harmonization, because many countries, including the US, failed to sign it. Nevertheless many of its provisions were later incorporated into the GATT agreement, through the Trade Related Aspects of Intellectual Property agreement (TRIPS), which was signed in 1993 by 100 nations. TRIPS established minimum standards for patent protection (e.g. an award period of at least 18 years) and enforced equal rights between domestic and foreign patentees.[9]

In respect to Europe, the European Patent Convention (EPC) was signed in 1978, establishing the European Patent Office (EPO). The EPO discloses applications after 18

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[8] The applicant had to file for a patent in his native land, in his native language, plus a later English translation of the application.

[9] TRIPS has been the center of criticism. For example, the theoretical literature, working on North v. South models of trade has cast doubts on weather TRIPS will succeed in fulfilling its main promise, which was to promote innovations (by introducing a tangible patent system) to third world countries, see, Deardorff (1991), Diwan and Rodrik (1989), Helpman (1993) and Lai (2001). Empirical doubts are also cast by, Lanjouw (1998 a), Lanjouw and Cockburn (2000). By contrast, Sherwood (1997) takes a far more positive approach towards TRIPS.

months, and the awards last for 20 years. Recognizing that the formation of the EPO was just a step towards a common goal (in the form of a unified and centralized patent system) EEC members agreed on the Convention for the European Patent for the Common Market, which was first agreed in 1975, amended in 1985 and 1989, but is yet to be fully implemented.[10]

Contrary to European patent systems the Japanese one is relatively recent. Specifically, in Japan patent law was first introduced in the Meiji era and many of its elements were modeled upon the German system.[11] After WWII, it was amended to incorporate a weaker novelty requirement and disclosure after 18 months. The JPO, up until 1988, issued very narrow patents, typically with only one claim and, since the judges frequently exerted pressure for settlements, patent litigation was lengthier than in Europe and the US. Due to US pressure, in 1989 Japan initiated the Structural Impediments Initiative, which led Japan (in 1994) to allow foreign applicants: to file patent application in English, to request accelerated patent examinations, and to stop threatening firms that refused to license their patents to rivals.[12]

The US case needs special attention, not only because it is the country where most of the latest innovations originate from, but because it has been the stage of recent drastic changes in patent practice, changes that are finding their way to other patent systems as

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[10] It calls for a centrally enforceable patent and a centralized appellate court. In 2003 it was decided that the court should be based in Luxemburg but that it should assemble in the country where the case originated. Even though this provision was supposed to start from the year 2010, it has already been slowed down by more objections from member states that view this agreement as cumbersome.

[11] See Forstner (1993).

[12] For a closer look at the empirical evidence concerning the Japanese patent reform see Sakakibara and Branstetter (2001).

well. In addition, the US is the only country where patent protection is constitutionally founded, being based on an exclusive rights clause (Article I.8).[13]

Overall, some of the main changes that took place in the last 20 years are the following:

a) in 1980 Congress passed the Patent and Trademark Laws Amendment (Bayh-Dole); this Act allowed universities to patent any innovations they had created with government funding.[14]

b) In 1980 the US Supreme Court extended patentability to genetically engineered bacteria (Diamond v. Chakrabarty).

c) In 1981 the Supreme Court held that software that was part of a manufacturing system or process was patentable (Diamond v. Diehr).

d) In 1982 Congress passed the Federal Courts Improvements Act. This Act allowed for the formation of a centralized appellate court, the Court of Appeals of the Federal Circuit (CAFC). As I will elaborate in a later section, the CAFC has been applauded by many on taking a tougher stance on patent infringement, basing its decisions (in addition to the traditional criteria of novelty, utility and non-obviousness) on market success considerations as well.[15]

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[13] For a criticism of Article I.8 see Kingston (2003).

[14] For an in depth analysis on university patenting and the effects of the Bayh Dole Act see, Henderson, Jaffe and Trajtenberg, (1998), Beath *et al.* (2003), Sampat, Mowery and Ziedonis (2003), and Poyago-Theotoky, Beath and Siegel (2002).

[15] The CAFC, when examining a patent infringement case, bases its decision on the following legal doctrines, a) the doctrine of disclosure and enablement: under the law disclosure must be sufficient to enable 'any person skilled in the art to make and use' the claimed invention (U.S. Code, 1988, Section 112). b) The doctrine of equivalents: The doctrine of equivalents states that '[I]f *two devices do the same work in substantially the same way, and accomplish substantially the same result, they are the same, even though they differ in name, form, or shape*' , (Supreme Court decision Graver Tank, 1950, at 668). c) The doctrine of reverse equivalents: this doctrine is fit for cases where, even though a devise fits under the claims of the litigant, it is

e) In 1984 Congress passed the Semiconductor Chip Protection Act, to protect microchip design.[16]

f) In 1998 the CAFC upheld a patent on a software system that performs real-time accounting calculations and reporting, which was to be used by mutual fund companies (State Street Bank & Trust Company v. Signature Financial Group). This decision allowed the patentability of business methods.

To the above one should also add the Drug Price Competition and Patent Restoration Act (Hatch-Waxman Act),[17] and The First American Inventors Protection Act of 1999.[18]

In order to put the above description of the patent system into perspective, in the rest of this section I will provide some descriptive statistics that shade some light on who patents what. On this, the study of Allison and Lemley (2002) is invaluable, not only because it offers a comprehensive study of 1000 utility patents issued in the US during 1996-1998, but also because it points out the differences between technological sectors, noting an overwhelming increase in the number of issued patents. Specifically, in the period under study, the patent office issued 147520 patents, a 45.4% increase over the number issued just three years earlier.

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so advanced that it should be excused. For further details, see Merges and Nelson (1994).

[16] In the process Congress created a new form of intellectual property rights, 'masked rights', for microchip designs. Accordingly, in order for a chip to qualify for masked rights it needs to display a degree of originality that is substantially lower compared to patents, see Hunt (1999 b).

[17] This Act restores up to 5 years of lost patent time spend on FDA testing. It also formally eliminates duplicative testing of generic drugs. Moreover, the first firm to file an application for making a generic equivalent to a branded drug receives a 180-day period of exclusivity, while manufacturers of branded drugs are allowed to request a 30-month postponement of the FDAs approval of generic drugs.

[18] This Act requires that all patent applications filed in the US and abroad be laid for public inspection 18 months from the earlier domestic or foreign filling date. Moreover, the Act establishes prior use defense against patent infringement charges for anyone who had reduced the subject matter to practice at least one year before the patent filing date and commercially used it prior to the filling date.

a) On average, each patent in this sample lists 2.26 inventors. From these patents 851/1000 patents assigned their rights to a corporate entity and 707/1000 patents were assigned to large entities. Of the 293 patents that were assigned to small entities, 118 were organizations (11 non-profits organizations and 197 small businesses), while individuals prosecuted the remaining 175 patents.

b) If one is to examine the size of patent applicants by technology area, most patent applications were filed by big firms. For example, out of 76 software patents, 5 were by individuals, 3 by small business, 2 by non-profits, 10 by small enterprises and 66 by large enterprises.

c) On average, these patents spent 2.77 years in prosecution, from the filing of the first US application to the issue date. The range of prosecution varied widely from a low of 1.16 years to 18.15 years. In all, prosecution time has increased, bearing in mind that Allison and Lemley (1998) found a mean of 2.37 years.

d) Taking a closer look per technology sector, software spends on average 3.15 years in prosecution, pharmaceuticals 4.46 and biotechnology 4.72. Overall, patents in the areas of chemistry, pharmaceuticals, software and biotechnology took significantly longer than average to make it through the PTO.

e) Each patent made reference to an average of 15.16 total pieces of prior art, the minimum being zero and the maximum number of references being 163. On average, each patent cited 10.34 prior US patents, compared with only 2.44 foreign patents and 2.37 non-patent references.

f) On average, patents in the sample had 14.87 claims, some patents had as few as one claim and as many as 120.

Concentrating on software patents only, Bessen and Hunt (2004) draw similar conclusions and show that there has been an overwhelming increase in the number of patents. In addition, contrary to expectations, the software industry is not the principal holder of these patents.[19] More macro statistics can be found in Jaffe (2000), who provides data on, patent ratios over time, US patent and R&D trends, patents from publicly funded research, publicly funded patents per dollar of research expenditure, biotechnology and software patents.

1.3 Patents and alternatives means for rewarding innovativeness

Patents are thought to be conducive to innovation as, by means of granting a state monopoly for a limited time, innovators can secure a return to his investment. The argument that competitive markets may not be beneficial to innovation has been familiar since at least the time of J. S. Mill[20] and was restated in the framework of the modern theory of market failure by

[19] In detail, 20000 software patents are now granted each year, compromising over 15% of all patents. The growth in software patents accounts for over 2% of the total growth in the number of patents between 1976 and 2001. Furthermore, compared to other technology sectors, software patents are more likely to be assigned to firms than individuals, especially larger US firms. They are also more likely to have US investors and they receive more citations from subsequent patents. Software patents are assigned to firms in a wide variety of industries. Most are assigned to manufacturing firms and relatively few are actually assigned to firms in the software publishing industry. This pattern conflicts with the simple view that firms are equally likely to obtain software patents to protect individual software inventions. BEA analysis of software investment (see Parker and Grimm (2000)) implies that about 30% of software is produced as package software, the primary product of firms in SIC 7372. Yet the software publishing industry acquires a much smaller portion of software patents.

[20] See Mill (1848).

Arrow (1962). Arrow (1962) was the first to suggest that competitive markets perhaps may not be beneficial to innovation. As Gallini and Scotchmer (2001) note, *'An invention....is a combination of tangible embodiments and an intangible idea....... Typically, both the information and the tangible embodiments are costly to the inventor, but only the tangible components are costly to the rival.'* Therefore, some protection is needed for the innovator, for without any protection the rival will be able to appropriate in full the innovation discouraging any research. This latter rationale has been questioned by Boldrin and Levine (2002), who in a stylized framework, where preferences remain constant, argue that innovative incentives can be sufficient even under a competitive environment, i.e. no or minimal protection. Their argument is centered on the assumption that the innovator will be able to charge a price for the initial copy of the product (which can then be freely reproduced at will) that covers his R&D cost. Hence, the monopoly that patents offer is far from a *sine qua non*.

As Abramowicz (2003) argues, many different methods of reward have been used in the past. One could note prizes[21] and grants. In recent days for example, the World Health Organization and the World Bank have suggested prizes for developing vaccines that mostly affect underdeveloped countries, and thus are not a top priority for pharmaceutical corporations. However, as Kremer (2001) suggests, there is a considerable amount of moral hazard and adverse selection involved in prizes and grants making such systems cumbersome to operate.

[21] To offer a historic example, in the 18th century the British government offered a prize for the most accurate method to calculate a ship's longitude at sea. John Harrison claimed the prize, after decades of delay.

By contrast, patents, being impersonal and resting on clear-cut criteria (novelty, utility and non-obviousness), do not carry such a risk. Nevertheless, patents create monopolies. Therefore, they create a dead weight loss to society. In addition, as Tabarrok (2002) explains, even though patents are needed for firms to recoup their R&D sunk costs, yet patents are not awarded on the basis of a firm's sunk costs. Because of the above deficiencies there have been many suggestions on how to create a better (or an alternative) patent system. For example, Kremer (1998) argues in favor of an auction, where the patent authorities take possession of the patent, auctioning it to the highest bidder. Assuming that firms can observe the true value of the patent, firms reveal this value in the course of the auction.

There have also been other less radical suggestions. For example, Aoki and Spiegel (1999) argue for an earlier disclosure of patent applications in order to facilitate a faster exchange of technology. Gilbert and Katz (2003) make a case for patents that allow for less claims, while Hunt (1999 a) concentrates on nonobviousness, suggesting that the recent trend (to decrease nonobviousness) can lead to less R&D activity. As he argues, this is more likely to occur in industries that rapidly innovate. Lastly, some researchers including Warren-Boulton, Baseman and Woroch (1994) and Cole (2001) are in favor of copyrights instead of patents for fast evolving industries such as software.

All the above views are centered on the way patents are awarded. Nevertheless, there have also been suggestions on how to promote R&D without changing the current system. The idea is to administer patents better, say through patent pools. An example may be the patent pool for DVD and MPEG patents; see Lerner, Strojwas and Tirole (2003) and Lerner and Tirole (2003). Needless to say, as Kultti, Takalo and Toikka (2002) argue, that the old debate on patents v. trade secrets is still on.[22] [23]

1.4 Do patents stimulate innovation?

On the basis of the criticism addressed in the previous section, the aim here is to examine whether patents act as a stimulant to innovation. As I will show, even though patents are far from being a panacea, in general they act as an incentive to innovate. However, their effect is sector specific. This section will elaborate on this by first concentrating on arguments that focus on how patents can stagnate innovation, and then look at arguments that find patents valuable. To this end, I will first focus on the empirical research that was carried out using patent counts and patent renewals,[24] and then discuss the findings of survey-based research. In the last part of this section I will pay attention to one of the main disutilities that are frequently associated with patents, i.e. patent litigation. As I hope to exhibit, the large cost associated with litigation can act as a barrier to innovation. Unfortunately, this last section will abstain from a much-needed theoretical coverage of patent litigation. Such an inclusion would drift this discussion too far into the territory of law. Nevertheless, the interested reader can find an introduction to US patent law in Besen and Raskind (1991), while Bentley and Sherman (2001) provide a thorough treatment of UK patent law. In addition, from an economist's perspective, the question of '*licensing v. litigation*' (which

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22 See also Denicolò and Franzoni (2002).

23 For an excellent introduction to trade secrets and trade secret law see Friedman Landes and Posner (1991).

24 For a detailed analysis of the methods and techniques used see Lanjouw, Pakes and Putnam (1996).

is always at the centre of any patent litigation case) is examined by Aoki and Hu (1998) and Crampes and Langinier (2001).

1.4.1 Do patents deter innovation?

A model of patent protection applied to a single, isolated invention postulates that stronger patents will induce more R&D investment; see Nordhaus (1969). There is no doubt that this model is a useful starting point, but it does not accurately depict many innovation processes. For example, if one is to look at some modern areas of research, say biotechnology, an interesting pattern emerges where some firms may control key research (and production) technologies, causing the research of other equally innovative firms to stagnate. Heller and Eisenberg (1998) have coined this effect the *'tragedy of the anticommons'*. Specifically, using the '*tragedy of the commons*' metaphor, which explains how people can overuse shared resources, they argue that in certain key technologies we are now faced with the opposite problem. People underuse scarce resources because too many owners can block each other. In other terms, stronger intellectual property rights may lead to fewer useful products for improving human health. Their argument finds support by Harrington (2002). He suggests that, since gene patents are awarded upstream in the innovative process, often long before a marketable downstream product is available, granting gene patents may promote the discovery of genes, but stifle any further research by effectively discouraging institutions other than the patent holder from thoroughly studying the gene. Lerner (1994), working on a sample of biotechnology firms, finds evidence of such behavior, where firms choose to redirect their innovative effort to technological areas in which prior art is not under strict patent control by rivals.

However, even if patent control is strict there is always an incentive to bypass the patent by inventing around it. Needless to say that in this case the ongoing duplication may not be welfare enhancing. To this end, as Gallini (1992) argues, extending patent life may increase an entrant's incentives to introduce an imitation during the patent period. Therefore, it may not much increase the value of a patent or, by the same token, the incentives to research. Even if inventions can be copied only after their patents expire, incentives to innovate may decline with increases in patent life. As Horowitz and Lai (1996) suggest, assuming that the inventor can develop higher quality improvements over time, then the relationship between the rate of innovation and the length of a patent will have an '*inverted-U*' shape. The mechanism behind this is the following: while an increase in patent life induces the researcher to develop larger inventions, inventions occur less frequently. Subsequently, for sufficiently long patents, the frequency effect dominates the size effect. As a result, the rate of innovation declines for increases in patent life.[25] [26]

Evidence of an '*inverted-U*' shape have been found by Lerner (2004). To be precise, Lerner conducts an international analysis of the relationship between patent strength and innovation, examining 177 policy shifts in 60 countries over 150 years. Lerner uses the fol-

[25] The result that further extensions in initially long patent lives may reduce overall incentives to research may also hold if subsequent researchers, other than the pioneer, are capable of developing the improved, patentable technologies, see Koo and Wright (2001).

[26] The model of Horowitz and Lai is one of the few models that directly examine the effects of patent protection on economic growth. Similar exceptions include, Kwan and Lai (2000), who use an endogenous growth model a la Romer (1990) in order to show that intellectual property protection in the US may well be too weak rather than strong, and Gould and Gruben (1996), who find evidence that intellectual property protection is a significant determinant of economic growth.

lowing four features in order to determine patent strength: a) whether protection existed in whole or in part for important technologies; b) the duration of the patent; c) the patent fee; and d) the existence of various limitations on patent awards (such as compulsory licensing). In this analysis the dependent variable was the growth of patent applications by residents in the country, while the independent variables include a dummy variable on whether the policy change is protection enhancing or reducing, and a dummy variable for the strength of protection prior to the change. Accounting for the above, Lerner finds some support for an '*inverted-U*' relationship between patent strength and innovation. This implies that, strengthening patent protection has a positive effect on innovation if protection is initially low and a negative impact if patent protection is initially high.

In addition to the above, nonobviousness has been one of the main sources of criticism against the patent system. Anecdotal evidence of patents that claim what everybody seems to already know is too numerous to account.[27] In theory, a patent must contain matter that is not obvious to anyone skilled in the prior art. However, as Jaffe (2000), Merges (1999) and Kesan (2002) argue, this rule seems to have been relaxed for some subject matter. Such a reduction in nonobviousness seems to be particularly true for software: see Hunt (2001), who questions the quality of many patent awards, observing that bad patents can block worthwhile innovation. As Judge Markey notes (Roper Corp. v. Litton Systems, Inc. 757 F2d 1266 Federal Circuit 1993), '*A patent is born valid and remains valid until a challenger proves it was stillborn or had birth defects*'; therefore it is up to the innovator, through litigation, to prove the merits of his innovation, while arguing that the

[27] There even exist newsletters that bring such patents to the attention of the interested reader, see: patnews@ns1.patenting-art.com.

blocking patent should not have been issued. As I will elaborate in a later subsection, litigation is a rather costly way to rectify the mistakes made by the patent office. To this reduction in nonobviousness one should also add the already noted increase in delays during patent prosecution by the patent office. It suffices to say that such delays can be costly for industries where technologies evolve at a fast rate, rending them obsolete very quickly.

Bessen and Hunt (2004) suggest that, for software, the patent system can even lead to a reduction in R&D, even though the number of patents increases. Specifically, using the software share of a firm's patents as a proxy for the cost of patenting, they find that software patents do substitute for R&D. Specifically, those firms that increased the share of software patents in their patent portfolios tended to reduce their R&D spending relative to sales in the 1990s. The magnitude of the substitution effect is significant. For example, at sample means, firms would have to spend 10% more on R&D if patenting standards had not been changed for software. Bessen and Hunt argue that these results point to an economically important reason why firms acquired software patents in the 1990s, namely a patent thicket strategy. Such a strategy concentrates on building a strong patent portfolio, one that will prove hard to bypass for any rival. Such a portfolio can act as a significant source of revenue, but above all it acts as a defense against similar portfolios.

Furthermore, as Bessen and Hunt note, prior to 1999 software patents tended to cost more than other patents; however, as they find, after 1990 software patents cost less that other patents and they are associated with proportionately larger patent portfolios for any given level of profits. In other words, changes in the cost of patenting software largely explain the recent widespread use of patents. This explanation for the recent surge in patent applications contrasts Kortum and Lerner (1997), who, by process of elimination, conclude that, even though the explanation behind the recent patent surge lies (as in Bessen ad Hunt) outside the patent system, this surge can be explained by an increase in the productivity of research.

1.4.2 Do patents promote innovation?

Turning my attention to the positive attributes of patents it is perhaps worthwhile to initially concentrate on whether patents act as a research promotion mechanism, i.e. a subsidy to R&D. Schankerman and Pakes (1986) using patent data from the UK, France and Germany find that at the aggregate level patent protection is a relatively small component of the incentive structure underlying private R&D investments. However, the distribution of the private value of patent rights is sharply skewed. There is a concentration of patent rights with very little private economic value, but the tail of the distribution contains highly valuable patent rights. In later research on patent renewal data from France, Schankerman (1998) finds that patent protection is a significant, but not the major, source of private returns to inventive activity and that its importance varies sharply across technology fields. To provide an example, even though on average patents are equivalent to a 15% subsidy on R&D these figures are 15-20% for mechanics and electronics.[28] Along these lines, Lanjouw (1993), using West German patent data, suggests that for her sample, learning is complete within 6 years, obsolescence is rapid, and the distribution of patent value is very skewed. To this line of research one should also add Lerner (1994). Specifically, Lerner, using a

[28] For similar results see Lanjouw (1998 b).

sample of 535 financing rounds at 173 privately held venture-backed biotechnology firms, develops a proxy for patent breadth based on the international patent classification scheme and shows that the breadth of patent protection significantly affects valuations.

Turning my attention to survey based research, one of the oldest studies carried out on the value of patents was by Mansfield *et al.* (1982), who surveyed 48 (patented and unpatented) product innovations of major US firms in the chemicals, drug, electronics, machinery industry. As it turned out, 60 % of patented innovations were imitated within four years of introduction. Nevertheless, this obsolescence seems to be sector dependant. This is also illustrated by Mansfield (1986), who asked the R&D executives of 1000 US manufacturing firms to identify the fraction of inventions developed by their firms that they would have chosen to develop had they been unable to patent. For electrical equipment, primary metals, instruments, office equipment, motor vehicles, and several other industries, these executives considered patents to be less important than a head start, and accordingly they would have proceeded with 90% of their innovations. One reason frequently quoted for this is that for new, rapidly changing technologies, patent information is largely outdated by the time it is granted (see Cohen Nelson and Walsh (1998)). This picture changes if one is to look at pharmaceuticals and fine chemicals. Executives in the pharmaceutical industry reported that without patent protection 60% of their new pharmaceuticals would not have been developed, and the reduction in other chemicals would have been about 40%.

In a seminal contribution, Levin, Klevorick, Nelson and Winter (1987) concentrate on how patents can increase production cost for imitators. They show that patents tend to raise imitation cost and time, and that these increases can be regarded as alternative indicators of the relative effectiveness of patents in different industries. Again there seems to be a lot of variation across industries. For example, patents raise imitation cost by 40 percentage points for both major and typically new drugs, by 30 points for major new chemical products, and by 25 points for typical chemical products. These figures are in accordance with an earlier study by Mansfield, Schwartz and Wagner (1981), which concluded that patents generally raised imitation cost by 30 percentage points in drugs, 20 points in chemicals and 7 points in electronics.

Protection is at the centre of a similar study by Cohen, Nelson and Walsh (2000), who turn their attention to the ways firms use to protect their intellectual property. Their principal finding is that although patents may have increased in importance among firms, they are still not one of the major mechanisms in most industries. Nevertheless, patents can act as a barrier to rivals. Specifically, Cohen, Nelson and Walsh observe that in addition to preventing imitation the most prominent motives for patenting include the prevention of rivals from patenting related inventions (i.e. patent blocking), the use of patents in negotiations and the prevention of suits. This latter view is supported by Hall and Ziedonis's work on the semiconductor's industry; see Hall and Ziedonis (2001).

It would perhaps be educational to elaborate on the methods and techniques usually used to achieve such protection. One method that is frequently observed, particularly in chemicals (apart from drugs) and other discrete product industries, is the combination of patents in order to build patent fences around some patented core invention. Such '*barricading*' involves the patenting (though not the licensing) of variants and other inventions that may substitute for the principal innovation in the hope to preempt rivals from introducing competing innovations. For example, in the 1940's DuPont patented over 200 substitutes for Nylon to protect its core invention, Hounsel and Smith (1988).[29] [30]

A second '*similar*' use of patents is observed in complex industries such as electronics, where in order to become (or remain) a major competitor, firms often amass large portfolios.[31] The fact that, in such industries, the same patents are often used for both blocking and negotiations, suggests that firms not only patent to protect their own technology, but to hold their rivals hostage by controlling technology that they need. For an in depth analysis of such patent thicket strategies, see Shapiro (2001).

To the amassing of patent portfolios for protection one must also add a new trend, one that became evident in the 1990's, where companies use their patent portfolios in a predatory fashion. For example, several companies, including Texas Instruments, Intel, and Wang Laboratories approach rivals demanding royalties on old patent awards. For instance, in 1991 Texas Instruments is estimated to have received 257$ million from patent licenses and settlements because of its general counsel's aggressive enforcement policy; see Rosen (1992).

Protecting one's intellectual property

The threat of patent litigation is by far not a new strategy (see Khan (1995) for a historical account) and in many cases firms end up in court over alleged infringement. It is

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[29] Turner (1998) documents the case of the Fan patent where DuPont patented an improvement on its already commercialized color proofing process for photographic film in order to prevent its preemption in the marketplace.

[30] Arora (1997) descries how chemical firms will sometimes protect an innovation by applying for one or more patents on different elements of an innovation, while keeping other elements secret.

[31] Therefore, it is of no surprise that of the ten firms receiving the most patents in 1998, nine are in the electronics industries.

thus to no one's surprise that patent litigation statistics seem to contain valuable information regarding innovation. After all, the decision to prosecute is an indicator of how valuable firms perceive their intellectual property to be, for if they did not consider it important they would have not litigated against possible infringement.[32]

To provide an example that shows how litigation can affect the value of a patent, Lanjouw (1998 b), working on patent renewal data from Germany, estimates that a doubling of legal fees could result in a 20-30% reduction in the mean value of patent protection in pharmaceuticals and other technologies. There is every reason to believe that there has been an increase in legal fees, mainly because there has been an increase in patent infringement cases,[33] initiated (as many argue) by the formation of the CAFC, which took a tougher stance against infringement. To see how this increase came about one has only to look at patent litigation data from the early 20th century.

Specifically, Federico (1964) provided validity and infringement data for litigated patents during the years 1925-1954. He found that courts upheld the validity of patents in only about 30-40% of the cases in which validity was an issue.[34] In a later study by Koenig (1980), with data from 1953-1978, district and circuit courts found patents valid about 35% of time.[35] The above pattern was to drastically change with the introduction

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[32] For a literature review on patent litigation see Lanjouw and Lerner (1997).

[33] For a report see, Korman (1998).

[34] He also concluded that prior art before the courts was often better than used by the PTO in issuing the patent, based on his observation that accused infringers were generally more successful in convincing courts to invalidate patents on the basis of incited prior art than on the basis of cited prior art.

[35] Koening collected all patent cases reported in the US PTO in the years 1953-1978 to produce an array of descriptive statistics. She also selected a random sample of 150 patents from the years 1953-1967 for more in-depth study. In addition to finding that most courts held patents invalid, and noting the wide disparity of validity rates across regional circuits, she also found that obviousness was the most frequent used basis for judicial invalidation of patents.

of the CAFC. This was because the CAFC raised the evidentiary standards required to challenge patent validity and broadened the interpretation of patent breadth, see Merges (1997). Furthermore, the court relaxed the requirement that patents be granted only for inventions that are not obvious to practitioners skilled in the art.[36] The above changes lead to a higher plaintiff success rate. Specifically, Harmon (1991) finds that from 1982 to 1990, the CAFC affirmed 90% of district court decisions holding patents to be valid and infringed, and reversed 28% of the judgments of invalidity and non-infringement. As a result the overall probability that a litigated patent will be held to be valid has risen to 54%, see Allison and Lemley (1998).[37] Subsequently, as Siegelman and Waldfogel (1999) note, the implied average expected likelihood that the plaintiff will prevail is about 35% for all patent cases, which is higher than all of the other categories except contracts.

Overall, as Jaffe (2000) observes, the litigation rate is 1% of all patents. However, there are large differences across sectors, with the likelihood of litigation in the drugs and health field being roughly double the overall average. Lanjouw and Schankerman (2004) report that, for their data sample, there are (on average) 19 case fillings per thousand patents. They also find a lot of variation between industries. For example, the lowest rates are found in chemicals (11.80), electronics (15.4), and mechanical (16.9). To the authors' surprise, filing rates for pharmaceutical patents are only modestly higher that the average. The rates are much higher for patents in other health, computers, biotechnology,

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[36] See Cooley (1994), Dunner et al (1995) and Lunney (2001).

[37] Allison and Lemley find that the probability of validity does not vary significantly by technology field, or the nationality of the inventor. They also note that the average final validity finding occurs about 9 years after the patent was granted and about 12 years after the application date. However, Waldfogel (1998) finds that cases that resolve in 3 months are won by the patentee 84% of the time and cases resolved within a year are won 61% of the time. This suggests that the fact that only half of cases carried to conclusion are won by the patentee greatly understates the likelihood that a random patent can be enforced.

and miscellaneous. Along these lines, Lerner (1995) finds that within biotechnology about 6% of all patents end up in litigation, while Lanjouw and Schankerman (1997) estimate that US patents from the early 1980's will, by the time they expire, generate more than one suit for every hundred patents.

If one is to take a more micro look at litigation statistics then a pattern emerges connecting litigation to size of patent portfolio and number of claims. The latest research on this topic is by Lanjouw and Schankerman (2004, 1997). They find that having a larger portfolio of patents reduces the probability of filing a suit on any individual patent in the portfolio. As they note, for a (small) domestic unlisted company with a small portfolio of 100 patents, the average probability of litigating a given patent is 2%. For a company with a similar profile but with a moderate portfolio of 500 patents the figure drops to 0.5%. However, the probability of litigation increases with the number of claims and forward citations per claim, and the effects are substantial. In addition, this portfolio effect is stronger for smaller companies, as measured by employment. It seems that, for small firms, having a portfolio of patents is likely to be a key mechanism for avoiding litigation. Lanjouw and Schankerman also find evidence of a threat value associated with having control over many patents in an area. This suggests that firms having portfolios that are large relative to the disputants they are likely to encounter are significantly less likely to make use of the courts.

Some of their lesser (but nevertheless important) findings can be summed up as follows,

a) Domestic listed companies are far less likely to prosecute infringement than unlisted companies and individuals.

b) About 80% of all suits that are ever settled are settled before a pre-trial hearing is held. Nearly all of the remaining settlement occurs before the trial commences. Specifically, post-filing settlement rates are about 95%, and most settlements occur soon after the suit is filed, often before the pre-trial hearing is held.

c) Win rates are close to 50%, while the mean litigation probability is 0.0135.

d) The main characteristics of patents and their owners do not affect the probability of settlement after a suit is filed, nor the plaintiff win rates for cases that reach trial. In addition, post-suit outcomes (the probability of settlement and the patentee win rates at trial) are almost completely independent of the agent-characteristics.

This negative link between size and patent litigation can possibly be the result of high litigation costs. In detail, as Merges (1999) points out, the expenses of conducting a patent infringement case can cost from 1$ million to several millions. If one is take a closer look at the total cost of patent litigation then the numbers are roughly one fourth of basic research expenses. Specifically, Lerner (1994) reports that, from July 1989 to June 1990, 1318 patent related suits were initiated in the US Federal Court and approximately 3900 procedures within the US PTO. He estimates, based on historical costs, that these cases will involve legal expenditures of about one billion 1991 dollars, which should be compared with expenditure on basic research of 3.7 billion by US firms in 1991 (i.e. 27%

of expenditures on basic research by firms that year).[38] Due to this high cost 55% of small firms and 33% of large firms report that litigation is a deterrent to innovation.

Along the same lines, Lanjouw and Lerner (2001, 1996) find that preliminary injunctions are a remedy that may be available only to financially strong plaintiffs.[39] [40] Moreover, legal expenses are likely to be higher for unlisted firms, which are typically smaller firms, and for individuals because of their greater reliance on external legal counsel. Direct survey evidence also supports this link between size and litigation. In their 1994 survey of 1478 managers of US R&D units, Cohen, Nelson and Walsh (2000) ask respondents to indicate the most important reasons, out of five possibilities, for not having patented recent innovations. These five reasons were, difficulty in demonstrating novelty, disclosure, ease of inventing around a patent, the cost of the application, and the cost of enforcement. In general, small firms believed that their patents were infringed more frequently, but were considerably less likely to litigate these perceived infringements.

But even for listed firms (which are typically of larger size) the burden is non-negligible. Specifically, Bhagat, Brickley, and Coles (1994) examine the market reaction to the filing of 20 patent infringement suits reported in the Wall Street Journal during the 1981-1983 period. They find that in the two-day window ending on the day the story appears in the Journal, the combined market-adjusted value of the firms fell by 3.1% on average. Lerner (1995), using data on 26 patents suits between biotechnology firms, finds an

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38 To the above cost one should add damages awards, which have increased since the formation of the CAFC, Merges (1997), Kortum and Lerner (1999).

39 In univariate comparisons, disputes in which preliminary injunctions are requested have plaintiffs almost twice as large, in terms of sales, employment, and cash equivalents, as those in disputes where preliminary injections are not requested. The plaintiff is also significantly more likely to be bigger than the defendant.

40 See also Cunningham (1995).

average fall of 2%. This represents a median loss of shareholder wealth of 20$ million. It suffices to say that if a defendant is unable to raise capital to finance the litigation through external capital markets, he may be forced to settle the dispute, no matter what the ultimate merits of his case are. In conclusion, litigation seems to be a powerful obstacle in protecting one's intellectual property, especially in cases where the litigant is of small size. This latter effect seems to be acknowledged by the EU, which commissioned a study on the problems that SMS EU firms face when protecting their patents in US courts; see Kingston (2000). This study, apart from acknowledging the high litigation cost, notes that juries tend to be more friendly to local (infringing) firms, forcing the plaintiff (the EU SMS) to take its case to a higher court. This latter choice is by definition a rather costly and lengthy alternative.

1.5 Designing an optimal patent

Having examined the role of patents as a stimulant or deterrent to innovation, this section will revisit the question of optimal patent design. Bearing in mind that patents are two dimensional, affirming their effects though patent length (which now stands at 20 years) and patent breadth[41] (the set of claims, and their adjacent technological territory, that the courts and the patent office consider to be fit for patent protection), the main problem that policy makers face is how to fine-tune these two different attributes in a way that best promotes innovation, while least reducing the public's social welfare. The starting point on any discussion of intellectual property must be the seminal contribution of Nordhaus (1969).

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[41] Also known as scope.

Nordhaus explained why patents should have finite length. His argument was that, assuming that the policy maker's only concern is to encourage innovation, then patents should last forever. However, if his sole concern is to avoid the deadweight loss (which is created by the monopoly that patents grand), then there should be no intellectual protection at all. A finite length of protection balances these two concerns. Nordhaus's work set forth a sizable literature on patent design, one that in broad terms considers patent races, imitation by rivals, technology licensing and how the design question changes when technology is sequential. With the above in mind, this section will first focus on patent breadth, concentrating at first on static technologies. In the second part of this section I will turn my attention to technologies of sequential nature.

Chronologically, Gilbert and Shapiro (1990) were the first to introduce the notion of patent breadth into the Nordhaus analysis. In Gilbert and Shapiro patent breadth is the price that an innovator is able to charge for the product that embodies the innovation. As they show, maximizing social surplus over all combinations of prices and patent lengths (combinations that yield enough revenue to cover the cost of R&D), optimal patent length is infinite and patent breadth should be set at the level that just covers R&D investment.

Gilbert and Shapiro's argument for patents that are narrow and long was first challenged by Gallini (1992). Allowing for costly imitation of patented innovations, Gallini's argument was that, with costly imitation a rival's decision to imitate depends on the length of patent protection. Therefore, the longer the patent life the more likely it is that rivals will 'invent around' the patented product. Extending patent life, therefore, may not provide the innovator with increased incentives for R&D. As it turns out, using both patent length and breadth as instruments, the optimal patent policy consists of broad patents with patent life adjusted to achieve the desired reward. That is, patents should be long enough to generate the required revenue for the patent holder, and broad enough to prevent imitation.

However, there is an important caveat in the above models, because this reversal depends on the absence of any assumptions about licensing. For example, in the Gallini model, if the patent is too long or too narrow, the innovator is assumed to watch inertly as imitators erode his market share. The question then is, can this duplicative waste be avoided voluntarily through licensing rather than by adjusting patent policy? As Maurer and Scotchmer (1998) point out, whatever the market outcome without licensing, the innovator and potential entrants can achieve the same market outcome through a licensing agreement with appropriate royalties. Since both the innovator and potential entrants can jointly save the imitation costs, they prefer licensing to imitation. In this argument, since there is always an unlicensed potential entrant, the licensor is worried about imitation by non-licensees as well as by licensees. Accordingly, the patent holder commits to a low market price precisely to reduce the attractiveness of entry by non-licensees.

Bearing the above in mind, it is worth analyzing whether licensing can potentially increase the market price. This can be achieved by considering the case of a single potential entrant, as in Gallini (1994). Specifically, Gallini suggests that with a single potential entrant (or a fixed number), the optimal licensing strategy is one of monopoly price with high royalties, and to share the revenues by using other fees. Thereby, the licensor has an incentive to keep the market price high regardless of the cost of imitation.

This section has up to now shown that, in a framework where goods are homogeneous and patent breadth governs market price, licensing prevents wasteful imitation. In this context, if licenses are available one can argue for narrow and long patents. By contrast, if licensing is not available, this analysis points to patents that are broad and short.

It suffices to say that for a variety of reasons licensing may not occur. This being the case, one needs a more thorough investigation of the arguments presented by Gilbert and Shapiro (1990) as well as Gallini (1992). Such an analysis is provided by Denicolò (1996). He explains that narrow (and long) or broad (and short) patents depend on the concavity or convexity, respectively, of the relationship between social welfare and post-innovation profit. Situations in which relatively short broad patents are optimal include costly imitation; a Cournot duopoly with constant marginal costs; and horizontally differentiated firms and linear transportation costs, as in Klemperer (1990).

The above discussion is limited to isolated innovations. A complexity that aroused interest from early on is that early innovators lay a foundation for later innovations. Thereby, a later innovation could not be made without the earlier one. Scotchmer (1991) was the first to contribute to this discussion. As she noted, in order for the first innovator to have enough incentive to invest, he should be given some claim on the profit of the later innovation. Otherwise, early innovators could be under rewarded for the social value they create. Therefore, the problem is how to divide profits between both innovators in a way that respects their costs. Otherwise, if all profits are allocated to the first innovator, the second inventor's incentive for research is reduced and vice versa. Green and Scotchmer (1995) argue that because of the difficulties in dividing profit, when innovation is sequential patent lives will have to be smaller. Furthermore, one needs not to alter patent design for the same result can be achieved with ex ante licensing i.e. licensing before investments are made.[42]

A danger of intellectual property, as Merges and Nelson (1990) point out, is that intellectual property can stifle innovation and slow progress because the monopoly awarded by patents deters further R&D into this technology. This negative attitude towards patents is countered by Kitch (1977), who argues that broad patents are socially beneficial because they stimulate further developments. However, there still remains an important issue concerning how these developments will manifest themselves in the absence of contracting/licensing from the original patent holder. This is at the center of Scotchmer (1991) and Green and Scotchmer (1995), who focus on how ex ante contracting affects the division of profits.[43] This theme is also advanced by Merges (1999), Scotchmer (1996), O'Donoghue, Scotchmer and Thisse (1998) and Schankerman and Scotchmer (2001). Lastly, Matutes, Regibeau and Rockett (1996) and Chang (1995) argue for broad patents even without assuming that ex ante contracts can be made.

Turning one's attention to the novelty that the patent office requires for a patent award, several arguments favouring both weak and strict standards for patent protection have been advanced. Green and Scotchmer (1990) argue for a weak novelty requirement standard. Under such a standard firms will be encouraged to disclose every small bit of progress. However, as Green and Scotchmer warn, while these disclosures could speed

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[42] To the above argument one should also add that, in a framework of sequential innovation statutory patent life is not as important. What matters is the effective life, that is, the time until the non-infringing substitute appears, see Scotchmer (1991), and O'Donoghue, Scotchmer and Thisse (1998). The effective life is determined by leading breadth, which is interpreted as the minimum quality improvement that avoids infringement.

[43] With ex ante contracting, the role of breadth is not to determine whether subsequent products are made (they will be made if they add to joint profit), but rather to determine how the profit is divided.

up invention by giving a technological boost to competitors, they can also encourage innovators to rest on secrecy instead of patents. By contrast, a tightening of the standards can encourage innovators to be more ambitious in the improvements they attempt to develop (O'Donoghue, (1998)). In addition, a tightening of the standards can affect the division of profit among sequential researchers. Scotchmer (1996) suggests that, as long as a second-generation product can be protected by an exclusive license on the infringed patent of the earlier generation, providing no protection for second-generation products would be in favor of the earlier innovators, without jeopardizing second-generation advances. Contrasting this view, Denicolò (2000), in a model in which firms race for the first and second-generation patents, shows that tilting profits in favor of earlier innovators might only encourage a socially wasteful patent race at the basic research stage and under investment in the second stage.

Notwithstanding the above, licensing is not problem free. First of all it raises antitrust issues. Furthermore, due to the *'anti commons'* problem licensing is likely to fail, see Heller and Eisenberg (1998). The sequential nature of innovation raises another issue. Licensing can suppress non-infringing follow-on products, reducing product-market competition. One should add that assuming such licensing occurred ex post (to prevent production of the cost-reducing innovation after it had been developed), it would be an antitrust violation. Chang (1995) analyzes that type of ex post collusion and is in favor of a strict antitrust rule against collusion. Lastly, Besen and Maskin (2000) argue that if firms do not license in a way that takes full advantage of their intellectual property (say because of antitrust restrictions), then licensing may reduce industry profits below those available without licensing, and the broad patents that support such licensing are counterproductive.

1.6 Conclusions

A well-known American proverb suggests that one should not try to fix something that is not broken. As the above sections explain, there are many problems associated with patents, enough to deem the patents system, possibly not broken, but, in any case, in need of treatment. These problems are related to the monopolistic nature of patents, as well as to inherent inabilities associated with the way such an elaborate apparatus is built and run. Nonetheless, assuming that the patent system is broken, does a better alternative exist? To be fair, the argument here is similar to the one that in many occasions is posed in favor of democracy. Indeed, the patent system may not be the best way to reward innovations, but is better than any other alternative that has so far been proposed or tested.

To illustrate these claims, I have reviewed the literature concentrating on the benefits and maladies of the patent system, paying special attention to the way litigation can stagnate innovation. In addition, I have asked the question of whether there is a better alternative to patents. The answer there is negative, if one is to consider only the radical proposals. However, according to more modest approaches, there is certainly a lot of room for improvements on the current patent system. Much of my effort has also concentrated on the optimal patent design, considering that patent protection affirms itself in two different directions, length and breadth. Again, as it turns out the literature has not yet provided a clear-cut answer to this riddle, even though the case for broad and short patents seems to be more persistent in its articulation.

I laboured my point using empirical results that have recently been available. These results include patent statistics as well as patent litigation statistics. All these data seem to overwhelmingly point out that in recent years patent protection has become a matter of great importance to innovators. However, these results do not have the capacity to indicate if this increase in patent awareness has also led to an increase in innovations. Even though, as the clock ticks, newer results are expected to come out, the seminal contributions by Jaffe, Trajenberg, Hall and Henderson (to name but a few), as included in Jaffe and Trajtenberg (2002), seem to indicate that in many cases this overwhelming increase in patent counts did not equally manifest itself in more or better innovations.

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Chapter 2
Understanding When Universities and Firms Form RJVs: The Importance of Intellectual Property Protection

2.1 Introduction

In the early 1980s, the Bayh-Dole Act enabled universities to patent their innovations easier than before. The purpose of the Act was to foster US innovative activity, especially between firms and universities, at a time when fears were mounting that the US was a technological laggard compared to Japan. There is no doubt that universities and firms had been jointly doing research well before the Bayh-Dole Act, Rosenberg and Nelson (1994). Nevertheless, the Act was successful in bridging many barriers between firms and universities, leading them to form Research Joint Ventures (RJV). Indeed there seems to be an increase in RJVs, not only between US firms and US universities, Baldwin and Link (1998), but, as figure 2.1 displays, between EU firms and US universities as well, Link and Vonortas (2002). However, as Hall, Link and Scott (2000) note, this increase is not as high as one would have anticipated. In explaining this shortfall in RJVs, Hall, Link and Scott (2000) stressed (among other reasons) the importance of Intellectual Property (IP) protection in setting obstacles to the formation of RJVs.

The aim of this chapter is to try to understand under what conditions firms are likely to form an RJV with a university and when can IP issues raise barriers. The theoretical literature on this issue is rather slim. With the exception of Beath *et al.* (2003) and Poyago-Theotoky *et al.* (2002), I am not aware of any other work, which studies the potential barriers in the formation of RJVs.

The thesis advanced in this chapter is that firms and universities, whose research is on new-technologies,[44] will find it easier to form such RJVs. A finding as such seems to be in line with evidence offered by Hall, Link and Scott (2001) and Link and Vonortas (2002). In explaining the above proposition, this thesis stresses the importance of the degree of IP protection. Specifically, this chapter shows that the optimal policy for a firm (university) that conducts research on a fast evolving and not well-understood technology (i.e. a new-technology) is to share it, by choosing to have a low degree of IP protection.[45] For example, when Bell Laboratories invented the transistor, which is a classic example of a new-technology, they licensed their patent to most competitors. At the time, Bell Laboratories recognized that they should forego some of their profits to benefit from the extended knowledge produced by spillovers.[46]

Keeping this in mind, when a firm (university) chooses to join an RJV, the firm must also account for its opportunity cost (the profits that it sacrifices by halting the research that it conducts on its own),[47] and the greater this opportunity cost is, the harder it will be for

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[44] Technologies that are closer to science and evolve faster than well-developed and well-understood technologies.

[45] This argument is similar to Ben-Shahar and Jacob (2001). However, in their study, the innovator may optimally choose a low IP protection policy to lock-in other innovators, who will be using his technology to innovate and hence monopolize the market.

[46] In an interview, the head of Bell Laboratories recognized that what they had invented was beyond their capacity. So they licenced it, for a small amount, hoping that their invention would bring returns in the form of *'angel dust'*. For a detailed account of the invention of the transistor see Rosenberg (1994), Mowery and Rosenberg (1989), and Nelson (1962).

[47] The firm (university) will stop its own similar research to avoid duplication. However, this does not imply that the firm (university) will halt its research altogether.

a firm to enter such a research partnership. However, as the above paradigm emphasizes, *'mature'* technologies will generate greater profits, because the firm does not have to share them. Thus, the opportunity cost for firms that already work on *'mature'* technologies will be greater. Thereby, firms and universities which conduct research on new-technologies will incur a lower opportunity cost, making them the most likely participants of an RJV. This finding is reinforced if one is to assume that universities concentrate their research only on new technologies.[48]

This line of thinking suggests that a large firm, operating many different research projects at the same time (thus being most likely to work on new-technologies among other things), should find it easier to form an RJV, because it would have a lower opportunity cost. This accords with the evidence presented by Caloghirou, Vorontas and Tsakanikas (2000), who find that firms that sell on average over 1 billion Euros tend to cooperate much more with universities.

In what follows, section 2.2 introduces the *'technology generating'* function, section 2.3 describes demand, while section 2.4 explains the maximization problem of the innovator, to be followed by sections 2.5 and 2.6 that find the optimal degree of IP protection and the conditions under which an RJV will be formed.

2.2 Technology

[48] Such an assumption is made by Beath *et al.* (2003).

2.2.1 An overview and some examples

In this section I will define, and provide examples, of the terms (such as innovation, RJV, university) that I will henceforth be using. In addition, I will present a summary of the way that individual innovators generate innovations and their objectives (the mathematical definitions will be provided in the sections that follow).

Specifically, heterogeneous innovators (firms) create patentable innovations, with a patent length of one year, through a discrete time technology generation process. At each point t in time, each innovator i creates an innovation, $\Delta A_{t,i}$. The definition of an innovation is the following, *'an invention* [which in my model becomes an innovation, a marketed technological advance] *is a new means of achieving some function not obvious beforehand to someone skilled in the prior art'*, Kline and Rosenberg (1986).[49] The sum of the innovations created by the innovator up to that time, makes the innovator's technology $A_{t,i}$. This is similar to many different quality ladders,[50] each one representing only one technology.[51]

Each innovator conducts research on only one technology. The technology that each innovator is working on will be a substitute to the technologies that the rest of the innovators are working on. In the context of a *'PC'* environment, one can think of such substitute technologies as the work of many individual innovators who at the same time try to create a better *'MP3 player'*, or a better *'Media Player'*. In this setting, the knowledge created by each innovator would be potentially beneficial to the research carried out by all other

49 The brackets were not included in the original.

50 See Grossman and Helpman (1991).

51 There is a considerable literature which explores the time technology generation process in situations where the R&D investment of the firm endogenously shapes technology. For a review see Baldwin and Scott (1987).

innovators in the form of knowledge spillovers; however, some form of tacit knowledge will be assumed, which does not allow an innovator to fully appropriate such spillovers. These knowledge spillovers are created when the innovator patents his innovation. Thereby, the work carried on the *'MP3 player'* can be beneficial to the innovator working on the *'Media player'*.[52] The objective of each innovator is to create a better technology, since, as it will become apparent in later sections, one increases the demand for his technology by improving it further.

I define patent breadth as the amount that an innovator can re-innovate around the technology of any other innovator (without being found guilty of copying one's technology) and thus use it in his research, in the form of knowledge spillovers, without paying any property rights. The larger the patent breadth is, the harder it is for an innovator to fully re-innovate around one's technology. In what follows, I will assume that if the patent breadth is equal to 1, then innovator i must make full use (and pay property rights) of the technology created by innovator j, $j \neq i$, similarly, if the patent breadth is 0, then innovator i can freely copy the technology created by innovator j, without paying any property rights.[53]

Based on the assumptions provided in the above paragraph, the patent breadth can neither be 0, nor 1. Specifically, having assumed the existence of tacit knowledge, the patent breadth cannot be equal to 0, because even if innovator j could freely appropriate the innovation of innovator i, he would still find it impossible to use it as well as its inventor.

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[52] Thereby, the technologies generated by the innovators are substitutes which generate spillovers that are complements. This assumption attempts to capture the multidimensional nature of innovation, where knowledge spillovers can be beneficial even though they may have been generated by a technology that is a substitute. This accords with the evidence offered by Hall and Ziedonis (2001), who study the microprocessor's industry, noting that firms use overlapping technologies, many of which have been discovered by other firms who share the same market.

[53] My definition of patent breadth corresponds to that of Denicolò (1996).

In addition, one should cancel out full IP protection, because in reality, due to spillovers, such a thing does not exist.[54]

In this framework, universities are research centers that specialize in both new and *'mature'* technologies. Through the term new-technology I imply a technology that is close to science. Such technologies have a large developing horizon, and they tend to move faster than *'mature'* and well understood technologies. A general example of such a technology would be software.

An RJV will be a partnership between the firm and the university, a partnership in which both partners decide in advance on how to split the gains and the cost of their research. Hence, I will assume that they form a very simple agreement, where each partner appropriates a set percentage of either gains and cost (this percentage does not have to be the same for either gains and cost).

For an innovator to innovate, he needs knowledge spillovers. However, unless one is willing to assume that all innovators are homogeneous in their innovative capacity, the knowledge spillovers generated by one innovator should not have the same effect on one's research, as those created by another innovator. This generates the problem of discriminating among the spillovers-generating capacities of many innovators, each working on different technologies. In order to account for this problem I will assume that a patent race takes place, in which each innovator races against a set *'target'*. In the setting of the *'Win-*

54 There is a large empirical literature pointing to this. For example, the research of Pakes and Shankerman (1979), has identified the effect that spillovers, diffused from major research centers (such as universities), have in fostering innovation. For the effects of academic research on innovation see Mansfield (1995), Jaffe (1989) and Zucker, Darby, and Armstrong (1998). In addition, Jaffe (1986) displayed the importance of the R&D spillovers, which are generated using a local pool of R&D, on the patent productivity of a firm. Spatial models as such can be found in Audretsch and Feldman (1996) and Kao, Chiang and Chen (1999).

dows' environment, a *'target'* could be the demand for an *'MP3 player'* that has double compressing ability. The ability of the innovator who works on the *'MP3 player'* to create such a player, will determine how useful his spillovers are to all the other innovators.

2.2.2 Technology generation

Technology is produced by risk neutral innovators, who employ a specific *'technology generating'* function. Specifically, there exist a continuum of innovators, operating in an economy that lacks a credit market, and faces no population growth, who create innovations $\Delta A_{t,i}$, using knowledge spillovers s, as well as some funding through past profits $\pi_{t-1,i}$.[55] However, accounting for the lag between the publication of the patent and the time that it spillovers into research, Pakes and Schankerman (1979), innovators will be using s_{t-1}. Overall, the innovations created by innovator i, $i \in [0, n]$, are generated through the following *'technology generating'* function,

$$\Delta A_{t,i} = s_{t-1}\pi_{t-1,i} + v_i, \quad v_i \sim (0, \sigma), \quad i \in [0, n] \tag{2.1}$$

The sum of the $\Delta A_{t,i}$, is a distinct technology line $A_{t,i}$, which is created by innovator i, having the following initial condition for $A_{t,i}$, $A_{0,i} > 0$, and no initial funding ($\pi_{-1,i} = 0$). Hence, $A_{t,i} = A_{0,i} + \sum_{1}^{t} \Delta A_{t,i}$. Equation (2.1) implies that s_{t-1}, π_{t-1} are substitutes that carry the same weight. Even though, this is a '*convenient*' simplification, there is no consensus among economists regarding the effect that spillovers have. Specifically, depending on the author, spillovers can account for 15% to 40% of an innovation, Griliches (1998).

55 In reality, firms can invest their profits, among other things, in capital stock, consumption and dividends to shareholders. However, since in this model no production function is specified and there is lack of shareholders and consumption, I am making the assumption that all past period's profits are used in innovating.

Furthermore, equation (2.1) suggests that in the absence of spillovers there is no $\Delta A_{t,i}$ no matter how big $\pi_{t-1,i}$ is. This assumption corresponds to the idea that no innovation can be created in vacuum and spillovers are essential and necessary when creating an innovation.

In equation (2.1), υ_i is distributed with mean 0 and variance σ, where σ is assumed to be exogenous. Due to υ_i, innovators who have similar (s_{t-1}, π_{t-1}) will not produce innovations of the same magnitude. In that respect, υ_i represents the innovator's ability to innovate. I will assume that even though the innovator knows his realization of υ_i, he is not aware of υ_j, $i \neq j$, until the race finishes. Hence, the innovator is unaware of the full magnitude of $\Delta A_{t,j}$. Since υ_i, can attain negative values it is possible for $\Delta A_{t,i}$ to be less than zero. If this turns out to be the case, it implies that research has followed a wrong path producing a technology $A_{t,i}$ that is less than past technology $A_{t-1,i}$. Accordingly, the innovator will not make use of $\Delta A_{t,i}$ in production, using his past technology instead.[56]

An example of a technology that did not generate the expected results, and in many respects was judged as inferior to its predecessor, would be High Definition TV (HDTV). In the late 1980's this was a promising European TV standard that turned out to be far more costly and outdated (when compared to the USA TV technology of its time).[57]

As I mentioned in section 2.1, each innovator aims at reaching some set *'goals/targets'*. These goals can be considered as the expectation of the society as to what it wants future technology to be. These goals can be set by either a governmental body or by a central

[56] Alternatively, in order to avoid $\Delta A_{t,i}$ having a negative value, one can assume that υ_i is lognormally distributed.

[57] In 1991 the European Commission, in an initiative that was backed up by various satellite interests, proposed an expensive plan, which was worth of 850 million Euro, to support the HDTV standard plan. There was considerable debate in the Council about the budget, but finally the issue was dropped, with the justification being that a more advanced technology was already available in the US. For a detailed discussion of the HDTV project see Braithwaite and Drahos (2000).

planner (who acts for the benefit of the society). An example of such a target set by the society (central planner) is the goal to create medication for AIDS. An example for a government set target would be the standards set in defence contracts. In both cases, innovators try to create innovations that can reach these targets.[58] Henceforth, I will use the general term *'social target'* in order to describe these *'goals/targets'*.

I will make the assumption that the expectation for future technology that society has (the *'social target'*), will depend positively on how innovative (in its capacity to produce innovations that have a greater ΔA) this technological sector has been (the MP3 industry in this case). This line of thinking suggests that, when dealing with a very innovative technological sector, society will have greater expectations for this technology, in comparison to the technology created by a less innovative technological sector.[59]

An intuitive example of such a *'social target'* is, $\Delta\phi_t = \alpha\left(\int_0^n \frac{\Delta A_{t-1,i}}{\zeta_{t-1}}dj\right)$, $\alpha > 1$. This equation, expresses the *'social target'* $\Delta\phi_t$ as a function of the average innovation created by all innovators $\zeta \in [0,1]$, $\zeta \leq n$, who managed to innovate at time $t-1$. In this setting, the greater the average innovation $\left(\int_0^n \frac{\Delta A_{t-1,i}}{\zeta_{t-1}}dj\right)$ is, the greater $\Delta\phi_t$ will be. In addition, a higher α indicates a technology for which $\Delta\phi_t$ moves faster. Allowing different technologies to have a different α, one can discriminate between technologies for which $\Delta\phi_t$ moves faster compared to others.

[58] For a similar assumption see Scott (1996, 1997).

[59] Taking the above argument into extremes, suggest that Say's law is at work here, since the supply of innovations will determine the expectations of the society as regards to what it wants the new technology to be. Schmookler (1966), in his survey of the innovations produced by the railway industry, notes evidence of this.

Returning to the paradigm offered in the previous section, a greater α allows one to model the central planner's goal for the MP3 technology (a new-technology) as faster moving compared to that of the steam engine technology (a *'mature'* technology).[60] In this context, $\Delta\phi_t$ is an indicator of how useful this technology is to society. In contrast to $\Delta\phi_t$, ΔA is a quantitative index which expresses the magnitude of the technology, when compared to its initial starting point A_0.

Each innovator will be endowed with a probability of reaching the *'social target'*. This probability will be exogenous[61] and it will be a function of the innovator's ability to innovate $p(\upsilon_i) \in [0,\ 1]$, where $Ep(\upsilon_i) \neq 0$[62] and $\frac{\partial p(\upsilon_i)}{\partial \upsilon_i} > 0$, $\frac{\partial^2 p(\upsilon_i)}{\partial \upsilon_i^2} < 0$. In this context, $p(\upsilon_i)$ (for simplicity p_i) describes by how far the innovator will advance, compared to the *'social target'*. If $p_i = 1$, then he will manage to create an innovation that is equal to the full magnitude of $\Delta\phi_t$, if p_i is less than one then his innovation will be $p_i\Delta\phi_t$. Hence, each innovator i is expected to generate an innovation of magnitude $Ep_i\Delta\phi_t$.

It should be noted that, if an innovator creates an innovation that is greater than the *'social target'* $\Delta\phi_t$, then only he will be able to fully appreciate his innovation. All the other innovators have a limited foresight, hence they will not be able to comprehend the innovation's full magnitude. In this case, the innovator will have created some tacit knowledge, in the form of an additional increment, that can only be used by him and it will not spillover to others.

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60 The steam technology, as David (1990) notes, was the main technology driving production until early in the 20th century.

61 Scott (1996, 1997) allows firms investing in R&D to generate innovations that aim for the social target, but instead of assuming the probability of success as exogenous, it is an endogenous function of the firm's R&D.

62 E is the expectation operator.

In this framework, the *'social target'* $\Delta\phi_t$, introduces a multidimensional tournament effect, that allows one to discriminate among otherwise homogeneous agents. Hence, each innovator competes not with others, but with an endogenous goal $\Delta\phi_t$. How well the innovator performs in such a race, depends on his ability to innovate v_i. Thereby, $p(v_i)$ displays how good the innovator's technology is. In other words, $p(v_i)$ is a weight indicating to the rest of the innovators how useful the innovator's technology is and how much of it should they use; i.e. $p(v_i)\,\Delta\phi_t$.

Assuming for simplicity that $n = 1$, the average spillovers that each innovator attains are equal to,

$$s_t = \zeta_t \Delta\phi_t \int_0^1 p_i dj \tag{2.2}$$

where ζ_t is the percentage of innovator's who actually innovate.[63] For simplicity equation (2.2) can be expressed as,

$$s_t = \zeta_t \Delta\phi_t \delta \tag{2.3}$$

where $\delta = \int_0^1 p_i dj$. Substituting this equation into the *'technology generating'* function, one can derive the expected innovation created by innovator i as,

$$E\Delta A_{t,i} = \zeta_{t-1}\pi_{t-1,i}\Delta\phi_{t-1}E\delta \tag{2.4}$$

2.3 Demand

This section will concentrate on describing the demand for a good that is produced using a specific technology in a frictionless Walrasian market of size M. In this economy, at

[63] Since $n = 1$, ζ_t equals the number of innovators who innovate as well.

time t, each innovator i, $i \in [0, 1]$ will produce one innovation $\Delta A_{t,i}$, which will be used in the production of one good. The good produced through the use of innovation $\Delta A_{t,i}$, will be consumed by a homogeneous mass of consumers who are infinitely lived, have identical additive preferences, defined over lifetime consumption and a constant rate of time preference r. Goods are substitutes, and innovations are assumed to be non-drastic. As a result, there is demand for all innovations.

Specifically, the value of the demand $Q_{t,i}$ for a good i, that has been manufactured through the use of the innovation made by the i innovator at time t, is given by the following expression,

$$Q_{t,i} = M \frac{\Delta A_{t,i}}{\int_0^1 \Delta A_{t,j} dj} \ , \ \Delta A_{t,i} \in (0 \ , \infty) \tag{2.5}$$

In the above equation, similar to Scott (1997), $Q_{t,i}$ depends in a positive fashion on the latest innovation developed by i, and in a negative fashion on the innovations created by the rest of the innovators, i.e. $\int_0^1 \Delta A_{t,j} dj$. Demand $Q_{t,i}$ does not depend on the level of technology $A_{t,i}$ because, bearing in mind that patents last for one period, A_{t-1} is common among all innovators, which suggests that consumers must concentrate only on the vintage attributes of this technology.

Furthermore, equation (2.5), implies that the total demand for all goods will be equal to M. If there is only one innovator i, $Q_{t,i}$ will also be equal to M, suggesting that this innovator will be able to appropriate the whole market. In general terms, equation (2.5) follows the intuition introduced by Dockner, Jorgensen, Long and Sorger (2000), who treat demand in the same fashion, albeit in the context of capital accumulation games, during which demand is a function of the accumulated capital of different agents.

2.4 The innovator's profits

In this framework, when an innovator creates an innovation he immediately patents his innovation and licences it to competitors for a royalty that is equal to the size of the innovation that they will be employing in their research. This being the case, if innovator i chooses to use $p_j \Delta\phi_t$ of the research that is carried out by innovator j, then he must pay him $fp_j \Delta\phi_t$ in property rights, where f indicates the price for using knowledge. Henceforth f is used as a numeraire, implying that innovator i must pay $p_j \Delta\phi_t$.[64] However, how much of $p_j \Delta\phi_t$ innovator i will make use of, will depend on the patent breadth z_t^2, where $0 < z_t^2 < 1$.

In what follows, I will assume that patent breadth is a choice variable for the innovator. In reality, patent breadth is set out by the patent office (and the courts). However, it is up to the innovator to seek litigation if he feels that someone has been freely using his technology. Thus, the amount of technology transfer that takes place is up to the innovator's discretion. Accordingly, what I am modeling as a choice variable is not patent breadth *per se,* but technology transfer. For this reason, I will use the generic term IP protection in order to describe how much of his technology the innovator decides to freely share.

Assumption 1: *The choice of z_t^2 applied by innovator i on his innovation, when licensing it to innovator j, will be the same to the one that innovator j chooses.*

This assumption implies that there exists some form of reciprocality among innovators. Hence, if innovator i licences his innovation to innovator j applying a z_t^2 degree of IP

[64] Henceforth, all variables will be expressed in terms of f.

protection, innovator j will reciprocate using a z_t^2 degree of IP protection towards innovator i.[65]

Following assumption 1, innovator i will apply a z_t^2 degree of IP protection to his innovation. Thus, innovator i will receive $z_t^2 p_i \Delta\phi_t$ in royalties by each innovator who uses his innovation, and at the same time he has to pay property rights that are equal to $z_t^2 p_j \Delta\phi_t$ to each innovator j whose innovation he makes use of. Assuming that ζ_t percent of innovators will choose to innovate, the average property rights that innovator i has to pay to the other innovators are equal to,

$$z_t^2 \zeta_t \Delta\phi_t \delta$$

in addition, innovator i will receive

$$z_t^2 \zeta_t p_i \Delta\phi_t$$

in property rights. In all, each innovator will derive some income, because his innovation ΔA_i is used in the production of the good i, moreover, he will benefit from the royalties that he receives from the other innovators who make use of his technology. However, he also has to pay some royalties in order to benefit from the research of others. Accordingly,

[65] Bessen (2002), and Shapiro (2001), have shown that many major firms have created patent thickets (patent portfolios) which they can use (if they chose to) to block, not just similar innovations, but also innovations that may follow alternative techniques. In reality, most firms seldom use their patent portfolios in order to block innovation, Teece (2000). Nevertheless, such patent thickets act as deterrents to any firm which may act as a challenger. This analysis seems to suggest that there exist principal agents who have the means and power to enforce their will. Thus, less prominent firms have no choice but to follow on the footsteps of the major ones.

Thereby, if the major patent portfolio holders choose to litigate a lot, the other firms are left with no other choice but to go to court. Similarly, if the major patent portfolio holders choose to avoid litigation, it is not to the interest of less prominent firms to litigate against them (for if they choose to go to court larger firms have two advantages: a greater patent portfolio, and more money, thus they should be the most likely to win any court case against them). In the light of the above, assumption 1 is not unrealistic.

the innovator's average gross income will be equal to,[66]

$$I_{t,i} = Q_{t,i} + \zeta_t z_t^2 p_i \Delta\phi_t - \zeta_t z_t^2 \Delta\phi_t \delta \tag{2.6}$$

However, as Segerstrom (1998) notes, as the technology level increases it becomes harder to innovate. This is because starting technologies are easier to comprehend, while the more they develop they increasingly need more and more expertise. Thereby, the innovator has to pay a cost c for innovating, a cost that must be proportional to the innovation. Accounting for such a cost implies that technological growth will not follow an explosive path, allowing for a steady state solution. In what follows, I will model such a *'technology development cost'* as, $\frac{c\Delta A_{t,i}}{s_t}$.

Using a formula as such implies that, the greater the degree of spillovers s_t that the innovator can attain (through the use of the work carried out by others) the less the innovation cost that he has to incur. In other words, the more the people working on one field, the easier it is for one to innovate. Including such a *'technology development cost'* in equation (2.6), equation (2.6) becomes,

$$I_{t,i} = Q_{t,i} + \zeta_t z_t^2 p_i \Delta\phi_t - \zeta_t z_t^2 \Delta\phi_t \delta - \frac{c\Delta A_{t,i}}{s_t} \tag{2.7}$$

where I assume that $M > 1$ and $c < 1$, so as for $Q_{t,i} > \frac{c\Delta A_{t,i}}{s_t}$, implying that the complexity of an innovation cannot be large enough to hinder innovation.

Assuming that innovations are dissimilar, only a few innovators will actually have a Q that is high enough to guarantee them a high income. This line of thinking implies that the amount of royalties paid to the innovator, i.e. $\zeta_t z_t^2 p_i \Delta\phi_t$, will be limited for the

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66 In both the property rights that the innovator receives, as well as the royalties that he has to pay, I have not included the innovator's own contribution $p_i\Delta\phi$, because they cancel out.

majority of the innovators. Consequently, some innovators will be adversely effected by the royalties that they have to pay, since their average gross income $I_{t,i}$ will not be greater than zero. This implies that an increase in the degree of IP protection z^2 would decrease the number of innovators who find it profitable to innovate; the ones whose average gross income $I_{t,i}$ is greater than zero.

Proposition 1 *There is negative relationship between the number of innovators who find it profitable to innovate and the degree of IP protection.*

Proof. Innovator i will find it optimal to innovate only if his gross income $I_{t,i}$ is greater than zero. This suggests that the following inequality must hold,

$$Q_{t,i} - \frac{c\Delta A_{t,i}}{s_t} > \zeta_t z_t^2 \Delta\phi_t \left(\delta - p_i\right)$$

Since I have assumed that $Q_{t,i} > \frac{c\Delta A_{t,i}}{s_t}$, and δ is greater than p for the majority of the innovators, both sides of the above inequality are positive. Thus, increases in z_t^2 imply that, for some innovators, the above inequality will not hold. Moreover, further increases in z_t^2 will affect a greater number of innovators. ■

This finding seems realistic, if one accounts for the increased litigation that accompanies broadening patent protection.[67] Furthermore, this proposition accords with the evidence offered by Lerner (1995), who finds that in the biotechnology industry, when firms are faced with a strong patent barrier, they choose to redirect their innovating effort to projects where the patents that competitors have will not pose as many problems. Indirect

[67] Galini (2001) reports that starting firms must be ready to spend 2-3 million $ in litigation, if they want to either use other people's patents, or protect their own. In addition, as Lanjouw and Schankerman (2001) note, *'for the most valuable drugs and health patents the estimated probability of litigation during the lifetime of the patent is more than 25%, and more than 10% in other technology fields. As a percentage of utilized patents, these litigation rates would be even higher'.*

evidence for this negative relationship is provided by Aghion *et al.* (2002). Specifically, measuring innovative activity through the use of a weighted patent index, they find that a non-linear (inverted U) relationship exists between innovation and market competition.[68] [69]

For mathematical convenience, I will assume that the number of innovators who find it profitable to innovate is equal to ϵz_t^{-1} where $\epsilon \in (0, 1)$.[70] Subsequently, if one substitutes equation (2.3) in equation (2.7), and replaces ϵz_t^{-1} in place of ζ_t, the innovator's average income will become,

$$I_{t,i} = Q_{t,i} + \epsilon z_t p_i \Delta\phi_t - \epsilon z_t \Delta\phi_t \delta - \epsilon^{-1} z_t \frac{c\Delta A_{t,i}}{\Delta\phi_t \delta} \tag{2.8}$$

In this framework, following Jones (2001), the innovator will not appropriate all of the income that is created from producing output $Q_{t,i}$. He will appropriate only a share $z_t^2 Q_{t,i}$. Hence, the innovator's average profits at time t are,

$$\pi_{t,i} = z_t^2 Q_{t,i} + \epsilon z_t \Delta\phi_t (p_i - \delta) - \epsilon^{-1} z_t \frac{c\Delta A_{t,i}}{\Delta\phi_t \delta} \tag{2.9}$$

2.5 The innovator's maximization problem

Innovators maximize their profits subject to their *'technology generating'* function. Their choice variable is the degree of IP protection z^2, and their state variable is ΔA. The innovator's *'technology generating'* function is given by $\Delta A_{t,i} = s_{t-1}\pi_{t-1,i} + v_i$. Accounting though for equation (2.3), this equation becomes $\Delta A_{t,i} = \epsilon\zeta_{t-1}\Delta\phi_{t-1}\delta\pi_{t-1,i} + v_i$.

68 Hence, after a point, fierce competition reduces the number of patents.

69 If one controls for firm effects by using bellow-firm-level data on R&D activity the inverted U relationship disappears, Scott (1993).

70 The assumption that $\epsilon \in (0, 1)$ is included so as to have $z^{-1} \in (0, 1]$.

However, $\zeta_{t-1} = \epsilon z_{t-1}^{-1}$, allowing one to express the innovator's *'technology generating'* function as,

$$\Delta A_{t,i} = \epsilon z_{t-1}^{-1} \Delta\phi_{t-1} \delta \pi_{t-1,i} + v_i \tag{2.10}$$

In all, the innovator's problem can be written down as,

$$\begin{aligned} & \max_{z^2} \sum_{t=0}^{t} \beta^t \pi_{t,i} \\ \text{s.t } \Delta A_{t,i} &= \epsilon z_{t-1}^{-1} \Delta\phi_{t-1} \delta \pi_{t-1,i} + v_i \end{aligned}$$

with initial condition $A_{0,t} = A_0 \to 0^+$. Bearing in mind that the innovator is not aware of δ, (because even though the innovator is aware of his v_i, he is not aware of the v that other innovators have until the race finishes) the innovator does not *a priori* know how good the research of any other innovator is, and how his research will spillover into his future innovations. Therefore, noting that $Ep\,(v_i) \neq 0$, the innovator must solve the above problem in expected terms. Accounting for equation (3.22), one can restate the innovator's expected maximization problem as,

$$\begin{aligned} & \max_{z^2} \sum_{t=0}^{t} E\beta^t \left[z_t^2 Q_{t,i} + \epsilon z_t \Delta\phi_t \left(p_i - \delta\right) - \epsilon^{-1} z_t \frac{c\Delta A_{t,i}}{\Delta\phi_t \delta} \right] \\ \text{s.t. } E\Delta A_{t,i} &= \epsilon z_{t-1}^{-1} \Delta\phi_{t-1} \pi_{t-1,i} E\delta \end{aligned}$$

Suppressing, henceforth, the expectations operator E and allowing M to be a large number, the steady state FOC can be expressed as,

$$\widetilde{z} \sim \left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}M} \int_0^1 \Delta\widetilde{A}_j dj \right) \tag{2.11}$$

where $\Delta\widetilde{\phi}$ is the steady state *'social target'*, and $\Delta\widetilde{A}_i$ is the steady state innovation of innovator i. From the steady state solution, it is clear that increases in the size of the steady state *'social target'*, or in the size of the market, will cause a downward shift in $\widetilde{z}$. Contrary to that, increases in the size of the market which the other innovators occupy (i.e. $\int_0^1 \Delta\widetilde{A}_j dj$), will cause an increase in $\widetilde{z}$.

The above discussion implies that markets where the technology progresses quickly[71] (i.e. the $\Delta\widetilde{\phi}$ is big) should allow for a small degree of IP protection.[72] This finding accords with Gort and Klepper's study of technology product life cycles. Specifically, they find that most of the firm's patenting takes place in the latter stage of its research and not during its early stages.[73]

2.6 When should RJVs be formed

In this section I will concentrate on deriving the conditions under which an RJV will be formed. I will work under the assumption that an RJV is a partnership between an innovator (a private firm) and a university. The objective of the potential partners would be to benefit from the technological expertise that the other partner has, or alternatively to benefit from the profits that the other partner has.

In this model all innovators start from a very low starting point $A_0 \rightarrow 0^+$, without any external finance. These innovators progressively develop their technology A_i by creating innovations ΔA_i, which they profit from. Hence, *ceteris paribus* the magnitude of ΔA_i, when compared to the one that the other innovators create, depends on the innova-

[71] The capacity of the model to allow the innovator to choose a low degree of IP protection when dealing with a fundamental technology, accords with the historical evidence offered by Rosenberg (1994), Mowery and Rosenberg (1989), and Nelson (1962), with respect to the invention of the transistor.

[72] For a detailed discussion of the effects of δ and $\int_0^1 \Delta A_j dj$ on the above equation see Panagopoulos (2003).

[73] Gort and Klepper, (1982).

tor's ability v_i, see equation (2.1). Accordingly, the main factor determining how well an innovator preforms, and how big his profits are, is v_i.

This intuition suggests that, if one of the potential partners is lacking capital and wants to benefit from the profits of the other partner, in developing some technology, then there must be a mismatch in the individual ability of each potential partner to innovate. Considering that it is irrational for a good innovator to jointly do research with a bad one, I will henceforth concentrate on the first objective -i.e. innovators and firms want to form an RJV to simultaneously benefit from the expertise that each other has.

In this context, the average profits of an innovator i, who has created, at time t, some innovation $\Delta A_{t,i}$, are given by equation (2.9). These profits include the gains that the innovator makes from his innovation $z_{t,i}^2 Q_{t,i}$, as well as the cost $\epsilon z_{t,i} \Delta\phi_{t,i} (\delta - p_i) + \epsilon^{-1} z_{t,i} \frac{c\Delta A_{t,i}}{\Delta\phi_{t,i}\delta}$, where $z_{t,i}^2$ is the degree of IP protection that the innovator would choose and $\Delta\phi_{t,i}$ depicts how fast $A_{t,i}$ is evolving. If an innovator forms an RJV with a university, the two partners must decide on how to split the gains and the cost. Assuming that they decide upon a simple form of contact, one that attributes to each partner a set percentage η_1 of the gains and η_2 of the cost, their contract should be given by the following set, (η_1, η_2), where $\eta_{1,2} \in [0, 1]$. This being the case, the average profits $\pi_{t,i}$ of the innovator must be the following,

$$\pi_{t,i} = \eta_1 z_{t,R}^2 Q_{t,R} - \eta_2 z_{t,R} \left[\epsilon \Delta\phi_{t,R} (\delta - p_i) + \frac{\epsilon^{-1} c \Delta A_{t,R}}{\Delta\phi_{t,R}\delta} \right]$$

where $\Delta A_{t,R}$ is the expected innovation that the RJV will create, $Q_{t,R}$ is the demand for the good produced using $\Delta A_{t,R}$, $z_{t,R}^2$ expresses the degree of IP protection that the RJV will choose, while $\Delta\phi_{t,R}$ expresses how fast $A_{t,R}$ is evolving.

However, to the above profits one must include the opportunity cost of the innovator. The opportunity cost of the innovator will be the profits that he would forego, if he chooses to stop working on his own technology $A_{t,i}$ and starts working on the technology that the RJV will develop.[74] This opportunity cost must be equal to,

$$z_{t,i}^2 Q_{t,i} - \epsilon z_{t,i} \Delta\phi_{t,i} (\delta - p_i) - \epsilon^{-1} z_{t,i} \frac{c\Delta A_{t,i}}{\Delta\phi_{t,i}\delta}$$

Accounting for the above opportunity cost, the overall net profits of innovator i are given by,

$$\begin{aligned} \pi_{t,i} &= \eta_1 z_{t,R}^2 Q_{t,R} - \eta_2 z_{t,R} \left[\epsilon \Delta\phi_{t,R} (\delta - p_i) + \frac{\epsilon^{-1} c \Delta A_{t,R}}{\Delta\phi_{t,R}\delta} \right] \\ &\quad - z_{t,i}^2 Q_{t,i} + z_{t,i} \left[\epsilon \Delta\phi_{t,i} (\delta - p_i) + \epsilon^{-1} \frac{c\Delta A_{t,i}}{\Delta\phi_{t,i}\delta} \right] \end{aligned} \tag{2.12}$$

Based on the above discussion and on equation (2.12), it is straight forward to derive a similar expression for the overall net profits of the university as well.

As expected, the above equation implies that the innovator (university) will base his decision, on whether to join an RJV, on the expected innovation $\Delta A_{t,R}$ that the RJV will create, as well as on the way that the partners will allocate both cost and gains i.e. (η_1, η_2). However, I have shown in the above section, that $z_{t,R}^2$ is case specific, and that it depends on how fast the technology evolves i.e. $\Delta\phi$. Thus, the innovator must also account for his choice of IP protection. Bearing the above in mind, one can show that the decision of the innovator and the university to form an RJV does not depend on the degree of the collective magnitude of innovations $\int_0^1 \Delta A_j dj$, nor on the size of the market M, but on $\Delta\phi$ (how fast technology is evolving).

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[74] I assume that the innovator will stop his research on $A_{t,i}$ in order to avoid duplication. However, this assumption does not imply that he will choose to stop his entire research on this technology.

Specifically, as the following proposition states, firms and universities that work on new technologies should find it easier to form an RJV. This result is derived under the assumption that universities are not different from firms, both in the way that they maximize profits, as well as in their research specialization; since they specialize in both new and *'mature'* technologies. If one is to make the more realistic assumption that universities specialize only on new technologies, then this result is reinforced.

Proposition 2 *Universities and firms find it easier to form RJVs that specialize on new technologies.*

Proof. *See appendix one.* ■

This proposition accords with the evidence offered by Hall, Link and Scott (2000, 2001), who note that *'universities are most likely to partner in new technological fields where R&D is closer to science',*[75] as well as Link and Vonortas (2002), who list the RJVs between EU firms and US universities. In detail, the data of Link and Vonortas, included in figure 2.2, shows that most RJVs take place in technical areas that one would consider as fast evolving science, such as telecommunications.

In reality, it is difficult to find which technical areas/industries can be considered as fast evolving science. One possible way is to find which industries are the most R&D intensive. Specifically, using the ISDB data set,[76] the most R&D intensive industries are

[75] The reason that the authors offer is that universities offer research awareness, i.e. a research insight that is anticipatory of future research problems and could be an obudsman anticipating and translating to all the complex nature of the research being undertaken.

[76] This is an OECD data set that records, among other things, R&D expenditures per 3 digit industry; which means that it does not fully cover all the technical areas listed in figure 2.2.

(intensity is defined as R&D spending per worker and is included in parenthesis next to the industry): transportation (1), computers (2), and telecommunications (3).

Another possible way is to find which industries are the most patent intensive (patent intensity is used to express the number of patents that are granted per year and it is listed in parenthesis next to the industry). In this case, using the US statistical abstract one can find that telecommunications/electronics (1), transportation (2) and chemicals (3) are the most patent intensive industries.

From the above, even though there is no doubt that my analysis just touches on this very interesting issue, a pattern emerges which suggest that telecommunications, computers, transportation and chemicals can be considered as technical areas/industries that use fast evolving science. All these industries (along with energy/environmental technologies[77]) are in the top of figure 2.2, having the majority of RJVs between EU firms and US universities.

In conclusion, such a line of approach indicates that firms which face a lower opportunity cost are the ones most likely to form an RJV. Hence, large firms (ones operating many different projects at the same time, some of which should be on new-technologies) and firms with financial resources (who don't care about the opportunity cost that much), would be the most likely candidates for such projects. The evidence offered by Caloghirou, Vonortas and Tsakanikas (2000), pointing to the fact that firms that sell by average over 1

[77] The ISDB data set has no records on the R&D spending for the energy and environmental industries. This is because of the ISIC code listing that ISDB uses which includes the above two industries in other industry listings. There is a similar problem with the data included in the US statistical abstracts.

billion Euros tend to cooperate much more with universities than firms who sell less, seems to offer support for the view expressed above.

2.7 Conclusion

In order to regenerate the country's R&D activity, which it was feared to be lagging behind that of Japan, the US Congress passed the Bayh-Dole Act allowing universities to patent their innovations more easily than before. However, the increase in RJVs between firms and universities, initiated by the Bayh-Dole Act, is not as significant as expected. This chapter studies the reasons why firms and universities find it difficult to form RJVs, stressing the role of IP protection.

In its decision to form an RJV or not, a firm (and a university) has to make a choice between continuing to work along its own line of research, or to jointly develop a technology with a university. The choice of the firm will depend on how big its opportunity cost will be. As this chapter shows, firms which already do research on new-technologies (i.e. technologies that are closer to science and are not yet *'mature'* and well-developed), have a lower opportunity cost, hence they are the most likely participants of such RJVs.

The explanation of this thesis is premised on the importance of IP protection. Specifically, as firms (and universities) choose their preferential degree of IP protection in a market where firms licence their innovations to competitors, IP protection proves to be case specific. In particular, the degree of IP protection chosen by the firm will depend on how fast the technology evolves. In this framework, if the technology is new (fast evolving and closer to science), the firm will choose to share it, choosing to have a low degree of IP protection. Hence, the profits of the firm will be lower than those of a firm developing a slow moving, but *'mature'*, technology.

The intuition behind the firm's choice rests on the increased knowledge spillovers from which the firm will gain, if it chooses a low degree of IP protection on a technology that is not yet well-developed to create *'quality'* goods. Thereby, the opportunity cost for a firm that specializes on *'mature'* and well-understood technologies will be greater than the one of a firm specializing on new-technologies.

Essential to the above argument is the assumption that firms make similar choices regarding their preferred degree of IP protection. In addition, I have allowed innovation to be partly driven by an exogenous parameter whose aim is to represent ability. These simplifications have greatly aided in simplifying the model but leave room for further research, hopefully in a model in which IP protection will be non-cooperative.

2.A Appendix one

In this proof I will concentrate on finding the profits of the innovator (a private firm) and the university, when joining an RJV. Since, by joining the RJV the innovator (university) enters into a contract which specifies how the cost and the profits are split, I will concentrate this proof on the best case scenario for the innovator and the university, and afterwards offer a proof for the more general case. Initially, I will concentrate on the innovator and then on the university.

The most preferable outcome for the innovator is the one where the innovator appropriates all the gains, while the university all the cost. Symmetrically, the worst case scenario is the one where the innovator appropriates all the cost, making negative profits; and thus decides to abstain from any RJV. Specifically, equation (2.12) shows that in order for a innovator to find it profitable to participate in an RJV, the following inequality must apply,

$$\begin{aligned}&\eta_1 z_{t,R}^2 Q_{t,R} - \eta_2 z_{t,R}\left[\epsilon \Delta\phi_{t,R}\left(\delta - p_i\right) + \frac{\epsilon^{-1} c \Delta A_{t,R}}{\Delta\phi_{t,R}\delta}\right] > \\ &z_{t,i}^2 Q_{t,i} - z_{t,i}\left[\epsilon \Delta\phi_{t,i}\left(\delta - p_i\right) + \epsilon^{-1}\frac{c\Delta A_{t,i}}{\Delta\phi_{t,i}\delta}\right]\end{aligned} \tag{2.13}$$

Allowing the economy to be on a steady state, and substituting equations (2.11), (2.5), in the above inequality, one can re-express equation (2.13) as,

$$\begin{aligned}
&\eta_1 \left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}_R M} \int_0^1 \Delta\widetilde{A}_j dj \right)^2 \frac{M\Delta\widetilde{A}_R}{\int_0^1 \Delta\widetilde{A}_j dj} \\
&-\eta_2 \left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}_R M} \int_0^1 \Delta\widetilde{A}_j dj \right) \left[\epsilon\Delta\widetilde{\phi}_R (\delta - p_i) + \epsilon^{-1} \frac{c\Delta\widetilde{A}_R}{\Delta\widetilde{\phi}_R \delta} \right] \\
&> \left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}_i M} \int_0^1 \Delta\widetilde{A}_j dj \right)^2 \frac{M\Delta\widetilde{A}_i}{\int_0^1 \Delta\widetilde{A}_j dj} \\
&- \left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}_i M} \int_0^1 \Delta\widetilde{A}_j dj \right) \left[\epsilon\Delta\widetilde{\phi}_i (\delta - p_i) + \epsilon^{-1} \frac{c\Delta\widetilde{A}_i}{\Delta\widetilde{\phi}_i \delta} \right].
\end{aligned} \tag{2.14}$$

Allowing for $\Delta\widetilde{A}_R = \Delta\widetilde{A}_i$ implying that the innovator will not suffer from a decrease in demand if he forms an RJV, the most profitable scenario for the innovator is the one where $\eta_1 = 1$, and $\eta_2 = 0$. This means that, by joining the RJV, the innovator gets all the gains from this new technology, without incurring any of the cost. If this scenario is true than the above inequality can be expressed as,

$$\begin{aligned}
&\left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}_R M} \int_0^1 \Delta\widetilde{A}_j dj \right)^2 \frac{M\Delta\widetilde{A}_R}{\int_0^1 \Delta\widetilde{A}_j dj} \\
&> \left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}_i M} \int_0^1 \Delta\widetilde{A}_j dj \right)^2 \frac{M\Delta\widetilde{A}_i}{\int_0^1 \Delta\widetilde{A}_j dj} \\
&- \left(\frac{1+c}{\epsilon\delta\Delta\widetilde{\phi}_i M} \int_0^1 \Delta\widetilde{A}_j dj \right) \left[\epsilon\Delta\widetilde{\phi}_i (\delta - p_i) + \epsilon^{-1} \frac{c\Delta\widetilde{A}_i}{\Delta\widetilde{\phi}_i \delta} \right]
\end{aligned}$$

Canceling out equal terms and rearranging, it is straight forward to derive the following inequality,

$$\frac{1}{c+1}\left(\frac{\epsilon^2\Delta\widetilde{\phi}_i\delta\left(\delta-p_i\right)}{\Delta\widetilde{A}_i}+1\right)>\left(\frac{\Delta\widetilde{\phi}_R-\Delta\widetilde{\phi}_i}{\Delta\widetilde{\phi}_R}\right) \tag{2.15}$$

Apparently, the right hand side of equation (2.15) displays the percentage difference between $\Delta\widetilde{\phi}_R$ and $\Delta\widetilde{\phi}_i$. If this difference is either zero, or negative, this inequality will always apply. Subsequently, equation (2.15) shows that the innovator's decision does not depend on the degree of market concentration $\int_0^1 \Delta A_j dj$, nor on the size of the market M. It only depends on

$$\left(\frac{\Delta\widetilde{\phi}_R-\Delta\widetilde{\phi}_i}{\Delta\widetilde{\phi}_R}\right)$$

i.e. how fast does the RJV's technology evolves, compared to the technology that the innovator is working on. This inequality will always be satisfied if $\Delta\widetilde{\phi}_i \geq \Delta\widetilde{\phi}_R$.

Cancelling out the assumption of the best case scenario, where $\eta_1 = 1$ and $\eta_2 = 0$, allowing though for symmetry $\Delta\widetilde{A}_R = \Delta\widetilde{A}_i$, the inequality included in equation (2.14) becomes,

$$\frac{\epsilon^2\delta\left(\delta-p_i\right)(1-\eta_2)\Delta\widetilde{\phi}_R^2}{\Delta\widetilde{A}_i}+(1+c)\eta_1>\frac{\Delta\widetilde{A}_i}{\delta^2}\left(\frac{\Delta\widetilde{\phi}_R^2-\eta_2 c\Delta\widetilde{\phi}_i^2}{\Delta\widetilde{\phi}_i^2}\right) \tag{2.16}$$

In order for this inequality to always hold the following must be true, $\Delta\widetilde{\phi}_i^2 > \frac{\Delta\widetilde{\phi}_R^2}{\eta_2 c}$. Bearing in mind that $(\eta_2,\ c) < 1$, this expression suggests that $\Delta\widetilde{\phi}_i$ must be much greater than $\Delta\widetilde{\phi}_R$. This implies that an innovator will find it profitable to form an RJV if he is working on a new technology for which $\Delta\widetilde{\phi}_i^2 > \frac{\Delta\widetilde{\phi}_R^2}{\eta_2 c}$.

Up to now I have concentrated on what determines the decision of the firm. Accordingly, I have excluded universities from the decision process. In what follows, I will apply the rationale developed above in order to find what factors determine the university's decision to join an RJV. In a manner similar to the above proof, I will allow a university to have an opportunity cost. Forming the university's problem in a fashion similar to equation (2.14), it is easy to derive that in the steady the following inequality must apply,

$$\frac{\epsilon^2 \delta\left(\delta - p_u\right)\left(1 - \eta_2\right)\Delta\widetilde{\phi}_R^2}{\Delta\widetilde{A}_u} + (1+c)\eta_1 > \frac{\Delta\widetilde{A}_u}{\delta^2}\left(\frac{\Delta\widetilde{\phi}_R^2 - \eta_2 c \Delta\widetilde{\phi}_u^2}{\Delta\widetilde{\phi}_u^2}\right) \tag{2.17}$$

where the subscript u, indicating a university, has taken the place of the subscript i, which indicated the innovator. Similarly, for this inequality to always hold the following must be true, $\Delta\widetilde{\phi}_u^2 > \frac{\Delta\widetilde{\phi}_R^2}{\eta_2 c}$. Thereby, if $\Delta\widetilde{\phi}_u^2 > \frac{\Delta\widetilde{\phi}_R^2}{\eta_2 c}$ is true, a university will always find it profitable to form an RJV. This inequality should generally be true for a large enough $\Delta\widetilde{\phi}_u$ i.e. for new technologies.

In conclusion, innovators that work on new technologies should find it easier to fulfill equation (2.17) and form an RJV with a university, in addition the same is true for universities. Therefore, one should expect universities and firms to find it easier to cooperate if they are both working on a new technology.

If one is to assume that universities specialize on new technologies, see Beath *et al.* (2001) for a similar assumption, then the above proposition will still apply. This is because universities, since they already work on new technologies, have a low opportunity cost. Using equation (2.17), It is straight forward to show that a low opportunity cost as such will make universities eager to participate in an RJV that concentrates on both new and *'mature'* technologies.

This is because the right hand side of equation (2.17) is negative, thus the inequality expressed through equation (2.17) always holds. On the other hand, as I have already explained, only innovators that incur a low opportunity cost will choose to join an RJV, and these innovators are ones that work on new technologies. Thus, if an RJV is to be formed, it will specialize on new technologies.

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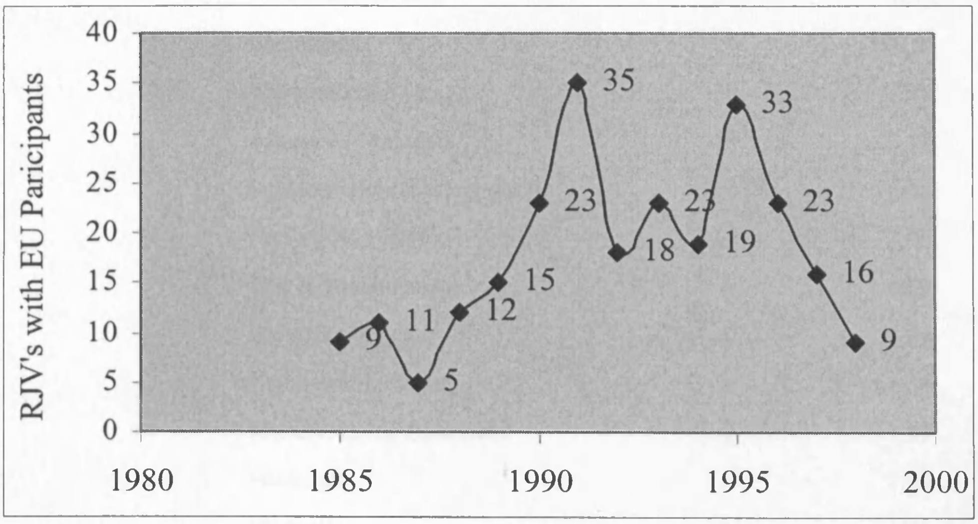

Fig. 3.1. RJVs between EU firms and US universities. Source, Link and Vonortas (2002).

Technical Area	Total RJVs 1985-1998	%
Telecommunications	40	15,94
Energy	32	12,75
Environmental	32	12,75
Computer Software	27	10,76
Chemicals	26	10,36
Transportation	20	7,97
Advanced Materials	19	7,57
Subassemblies & Components	14	5,58
Factory Automation	10	3,98
Test & Measurement	6	2,39
Biotechnology	5	1,99
Computer Hardware	4	1,59
Manufacturing Equipment	4	1,59
Photonics	4	1,59
Medicals	3	1,20
N/A	3	1,20
Pharmaceuticals	2	0,80
Total RJVs	251	100

Fig. 3.2. This figure includes the number of RJVs between EU firms and US universities, Link and Vonortas (2002).

Chapter 3
Patent Protection as a Stimulant for Risky Innovation

3.1 Introduction

The idea that a competitor's breath behind one's back forces tournament contestants to adopt riskier strategies is not a new one. It goes back to Harris and Vickers (1987) and Beath, Katsoulakos and Ulph (1989). Nevertheless, this idea has not yet found its way into the intellectual property protection literature, eventhough there is a well known historic precedent that displays how lack of competition can lead an innovator to rest on his laurels. Specifically, in the 1890s Edison successfully patented his light-bulb filament invention; however, until the patent expired, General Electric did not improve on this technology. In addition, even though other companies had created a better light bulb, General Electric managed (through successful litigation) to keep competitors out of the market, increasing its market share and sales.

In the light of the above argument, this chapter is based on a tournament between two competing innovating firms, where an innovation is a twofold process, based on prior art and risky experimentation. These two firms innovate sequentially and the winner is the only firm to put its innovation into production. The variable of choice for the firm is the amount of R&D effort that will be diverted to risky research paths, i.e. research that can lead to breakthroughs, as well as pitfalls. The production side of the economy is a simple growth framework based on Aghion and Howitt (1992). Within this context, the role of a central planner (who acts on behalf of the courts and the PTO) is to maximize production, using patent breadth as his choice variable. Patent breadth is indicated by how much the losing firm can copy (within the boundaries of legal protection) the winner's innovation. Overall, if the loser can fully copy the winner then they both have a similar technology at hand, which indicates that there is more competition between them during the tournament. Patent breath in this model is best captured by the number of patent claims allowed by the PTO, as well as the courts' attitude towards infringement.

The literature connecting growth theory to intellectual property is rather slim, see Gallini (2002) for a survey. A notable exception, from a theoretical point of view, is Horowitz and Lai (1996) who show that there is an inverted U relationship between the rate of innovation and patent length. The argument that they present is that an increase in patent length leads to larger, but less frequent, innovations. Moreover, from an empirical perspective, Lerner (2004), in an international analysis of the relationship between patent strength and innovation, examines 177 policy shifts in 60 countries over 150 years and finds some support for a non linear relationship.

Notwithstanding the above, when one is working on tournaments, in which innovators innovate in a specific technology, he must be careful when addressing the nature of the technology in use and the ability of the innovator, because sometimes the above-mentioned idea may not be applicable. For example, certain firms (economies) may not be in a position to successfully incorporate more risk into their innovating effort. By the same token, some technologies, such as the internal combustion engine, or sailing ship technology, are understood to have reached the end of their evolution, contrasting new technological paradigms, such as biotechnology. For the latter technologies the adaptation of risky innovation strategies may lead to unexpected results, while risky strategies in the former give relatively foreseeable results.

Overall, the aim of this chapter is to study optimal patent breadth, the one that maximizes production. As this chapter shows, there is an increasing relationship between how strong the optimal patent protection should be (patent breadth) and the ability of the economy (firm) to successfully follow risky innovation strategies. In an analogous fashion, new technological paradigms may require stricter protection compared to more mature technologies, where risky innovation paths may prove less productive. Bearing in mind that developing economies lack the capacity to successfully follow risky innovation strategies, this finding suggests that developing economies should adopt a more lenient intellectual property policy, compared to the ones followed by more advanced economies.

The notion of patent breadth differs from the ones used in the literature. For example, Gilbert and Shapiro (1990) suggest that a greater breadth is one that increases the flow rate of the innovator's profits, while Klemperer (1990) concentrates on the quality advantage of the patent holder. In addition, Gallini's definition, Gallini (1992), is one involving the cost of imitation, while Green and Scotchmer (1995) focus on the division of profits. In broad terms the definition of patent breadth suggested here is closer to Matutes, Regibeau and Rockett (1996), who also concentrate on new technological paradigms.

This chapter is not the only one examining patent breadth in the context of a tournament.[78] Tournaments have also been studied by Denicolò (2000 and 1996). However, the emphasis here is on the patent breadth that maximizes output. Therefore, the model distances itself from Denicolò (2000), Chang (1995), Gilbert and Shapiro (1990), Klemperer (1990) and Nordhaus (1969) who concentrate on social welfare.

This model is not without its limitations. Specifically, to simplify the analysis the model considers a static problem. Therefore, it cannot shed light on issues such as leading and lagging breadth, as in O'Donoghue, Scotchmer and Thisse (1998). Moreover, the model examines only patent breadth and it does not allow for a discussion on patent length. Such a simplification allows for results that are less prone to interpretation. Furthermore, the treatment of risk is effectively the simplest possible, hence there is no varying degree of risk. In addition, following a risky innovation path does not carry an extra cost. These essential complications are unfortunately left out for future research.

In what follows, sections 3.2-3.3 introduce the model, section 3.4 elaborates on the ways patents foster innovation, while section 3.5 derives the optimal patent protection.

3.2 Introducing the general framework

In this section I will first sketch out the benchmark model, as well as the main assumptions that accompany the growth model that is to follow, and then I will outline the model's main assumptions on how an innovation is created. Specifically, the model of Aghion and Howitt (1992) (explained in detail in Appendix one) is a model of endogenous growth,

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[78] For a review of tournament models see Reinganum (1989).

where innovations arrive stochastically. In this model, similar to most endogenous growth models, innovations are created in a monopolistic environment (protected by a patent), while the final product is produced in a perfectly competitive environment. This patent-based protection is shared by most endogenous growth models, making this general type of models better suited for the study of patents and economic growth.

One of the main characteristics of the Aghion and Howitt (1992) model is that an arriving innovation replaces the old one with certainty. Hence, the model captures the Schumpeterian notion of creative destruction, contrasting other endogenous growth models, such as the Grossman and Helpman (1991) model, where an innovation is a creative step that builds on all the existing prior art. Another important element of the Aghion and Howitt (1992) model is that it implicitly introduces a patent race framework in the way it derives the amount of labour devoted to research. One of the many insights offered by this model is that in the steady state the average growth rate of the economy depends on the number of research workers that the economy has.

Accounting for the above, the creative destruction that Aghion and Howitt introduce makes their model better suited for the present research. This is because this model already incorporates a limited time span for an innovation, similar to the limited time span that patents have. Segerstrom *et al.* (1990), also account for creative destruction. However, their framework is basically a North-South model of trade, unfit for the quality ladder framework that follows.

With the above in mind, I will assume two innovating firms i, j that operate in an economy with no credit markets. These two firms have full information about each other.

This economy is inhibited by a continuum of infinitely-lived individuals, with identical intertemporal additive preferences defined over lifetime consumption and a constant rate of time preference $r > 0$. Furthermore, only three classes of tradeable objects exist. The first one is labour, the second one is a consumption good and the third one is an intermediate good. Assuming no disutility from supplying labour, there is one category of labour (excluding the innovating firm, which can also be assumed as a an innovator), unskilled labour x. Unskilled labour can be used in the production of the intermediate good and as a producer of the final consumption good. Unskilled workers are all equipped with one unit of labour.

Innovating firms and production workers split the profits and, since no credit market exists, unskilled workers consume their wage at each instant. Specifically, the innovating firm keeps a set fraction $1-\epsilon$ of the profits, $\epsilon \in (0,1)$, while production workers receive the remaining ϵ. This fraction will be assumed to be exogenous. This exogeneity is introduced for two reasons. First, production workers and innovators (innovating firms) do not have the same skills, thus they are not homogeneous. Therefore, it is difficult to justify a labour market condition where, similar to Aghion and Howitt (1992), both parties receive the same wage, which is based on the value of the innovation. In addition, if one introduces a similar labour market condition making it endogenous to the model's main variable of interest (the patent breadth), then the results of the chapter would be introduced via the labour market, when, as far as I know, there is no empirical data in support of such an argument. Nevertheless, one can assume, similar to Jones (2001), that the greater patent breadth is the greater the monopoly power that the innovator enjoys, which increases his bargaining power and his share of the profits. Hence, ϵ could be endogenous on patent breadth. However, introducing the above argument in the model does not alter the model's final results and formulas. Thus, I will allow ϵ to be exogenous.

As regards to innovation, firms carry out research programs that result in a sequence of innovations. Each innovation is drastic and it consists of the invention of a new intermediate good, which is produced using x unskilled workers. The use of the intermediate good as an input allows more efficient methods to be used in producing a consumption good. However, only one firm will produce an intermediate good, with a tournament being the mechanism that determines which one. The intermediate good that the winner of the tournament produces will increase technology A by a factor of ΔA. This means that technology is sequential in nature. Thus, technology A is the sum of all past innovations $\sum \Delta A$.

In this framework, with certainty only one innovation will be developed every period t,[79] where t also corresponds to the ranking of each innovation. In view of the above, one tournament will take place every period. The winner of each tournament, the firm that has the greater A, will be a monopolist since it will be the only one whose intermediate good will be used in producing the final consumption good. Since innovations and tournaments must coincide, the index t will also be used to indicate the ranking of tournaments and of winners.

The model assumes that the winning firm patents its innovation and does not licence it. If the firm does not patent its innovation, since there is full information, the rival firm will

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79 This assumption accords with the evidence offered by Panagopoulos (2004).

be able to appropriate it. This patent, along with the intermediate good, will be employed by the firm in production, where production takes place in a perfectly competitive market (alternatively one can assume that the innovating firm sells its patent to a producer who operates in a perfectly competitive environment). The time span of the patent is assumed to be at least one period long.

If the winner of tournament t is i, then i will create an innovation that increases its past technology $A_{t-1,i}$ by $\Delta A_{t,i}$. The firm that failed to win, the follower j, will not be able to use $\Delta A_{t,i}$. This is because the patent of the winner on $\Delta A_{t,i}$ does not allow such use. However, j can re-innovate around $\Delta A_{t,i}$. This means that j can legally bypass some aspect of the winner's technology and by doing so it can legally develop some technology of its own. This re-innovating will take place during the $t+1$ tournament. In this context, j will be able to advance its past technology $A_{t-1,j}$ by $\max\{\Delta A_{t,j}, \lambda \Delta A_{t,i}\}$, where $\lambda \in [0,1]$ indicates how much re-innovating around $\Delta A_{t,i}$ the follower can do.[80] Therefore, the technology of j at time t is,

$$A_{t,j} = A_{t-1,j} + \max\{\Delta A_{t,j}, \lambda \Delta A_{t,i}\} \tag{3.18}$$

Accounting for the above, $1-\lambda$ can be considered as patent breath. For example, if λ is zero then the follower cannot re-innovate around the innovation of the winner. On the contrary, if λ is one then the follower can fully re-innovate around. This means that the follower will end up with an innovation that is of equal size to that of the winner.

[80] US law has an experimentation exemption. However, here the winning innovation leads directly to a final product. Therefore, any re-innovation will translate itself in a commercial product and this is prohibited.

The model's time-line is the following. Every period a tournament t takes place during which i, j create an innovation in the form of an intermediate input. All research oriented decisions (such as what type of research path to follow) will be taken during the tournament. After the tournament, the winner uses its technology in producing the consumption good.

3.3 Innovations

In this section I will model innovation as an ongoing twofold process. On the one hand an innovation will be the result of research that is based on prior art. This type of research should create an innovation of expected magnitude since it is the creation of techniques whose potential and limitations must be well understood. On the other hand, an innovation can be the result of experimentation. When one experiments he is working on the frontier of science where prior art is seldom in existence. Due to the lack of prior art and the absence of a full understanding of the potential of technologies on the frontier of science, the outcome of this research is uncertain.[81] Henceforth, I will use the term fundamental research to describe the research that takes place in such a situation.

An example of an innovation, which in its development involved fundamental research, is the invention of the transistor by Bell Laboratories in 1947. The aim of this research was to create a better electron emitting diode, one that was superior to the traditional *'bulbs'* that were in use at the time. From its start, Bell Laboratories had two choices, to either continue working on the traditional diode and try to improve it. Or, alternatively, try

[81] For a discussion on the uncertainty surrounding innovation see Rosenberg (1996).

and concentrate on an entirely new line of physics, namely solid-state physics. Solid-state physics, had only been introduced in the graduate curriculum of the top US universities in the mid 1930s and at the time there was little understanding (and a lot of uncertainty) involved around its potential. Therefore, solid-state physics was a research path that could have provided a dead end result. Successful, as it turned out to be, it led to applications that at the time where beyond the imagination of the creators of the transistor.[82]

However, in addition to the work that Bell carried out on solid-state physics applications, a great deal of the research that led to the invention of the transistor was supplemented by the use of well understood technologies. For example, in order to put theory into use Bell had to work on well known metallurgy technologies, which were needed in order to create the silicon *sandwich* material in which the transistor is bonded into.[83]

Accounting for the above, firm i has a choice on the way it uses its research effort (e.g. the time spent on research during tournaments) which for simplicity is normalized to one for both i and j. On the one hand, i can choose to work on a research path that uses traditional methods and techniques, which generate a fully expected and linear-increasing innovation. Alternatively, it has the choice to work on a research path that uses fundamental research (suggesting that results can vary both upwards and downwards and thus the nature of the resulting innovation is unforeseen). Accordingly, i splits its research effort between

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[82] The transistor was, at the time, perceived as an innovation with limited potential. In fact, Bell was initially hesitant on applying for a patent.

[83] Many of the subsequent improvements on the transistor, even to this day, have been based on improving this *sandwich* so that it allows less current to pass through, while permitting finer and more even transistors to be manufactured.

the two different research paths, spending $\sigma_{t,i} \in (0,1)$ in the latter research path and $(1 - \sigma_{t,i})$ in the former.

As indicated above $\sigma_{t,i} \neq 1$. This is because even for the most novel innovations one must make use of prior art by using tools and techniques developed in the past (traditional methods). In addition, $\sigma_{t,i} > 0$. This assumption accords with everyday experience, which suggests that some experimentation is always needed and cannot be avoided.

As regards the linear part of the innovation, the productivity of research is set as $\gamma > 0$. Thus, if during tournament t firm i uses $(1 - \sigma_{t,i})$ of its research effort on traditional techniques, there will be a linear set increase $(1 - \sigma_{t,i})\gamma$ in the magnitude of technology $A_{t,i}$. This increase in innovative capability is attributed to learning by doing and the knowledge spillovers generated by other technologies. Since the research of j must also spillover to i, one should express γ as a function of $A_{t,j}$. However, Pakes and Schankerman (1979), suggest that knowledge does not spillover spontaneously and that research takes 2-3 years to spillover. On account of this *considerable* time lag, noting that both firms have full information about each other and operate under the same patent system (revealing the details of all new innovations) I will treat γ as an exogenous parameter that is common for both firms.

Overall, γ is designed to capture the economy's increase in research productivity that does not result from fundamental research. If one is to provide a historical example, γ can account for the overwhelming increase in efficiency of the methods used to built the Liberty ship during WWII. This shipbuilding project was carried out in many different US shipyards, owned by different firms, over a four year period, under the guidance/control of the US ministry of defence, see Thorton and Thompson (2000).

Adding to the linear increase described above, there will be an innovation of magnitude $\sigma_{t,i}v_i$, where v_i is distributed having an exogenously given mean $\mu_i \geq 0$. This innovation is the result of fundamental research. In this model μ_i expresses the ability of i to successfully carry out fundamental research.

In total, the innovation created by i is given by,

$$\Delta A_{t,i} = (1 - \sigma_{t,i})\gamma + \sigma_{t,i}v_i$$

having an initial value of $\Delta A_{t=0,i} > 0$. The above formulation treats $(1 - \sigma_{t,i})\gamma$ and $\sigma_{t,i}v_i$ as perfect substitutes. In reality, $(1 - \sigma_{t,i})\gamma$ is the expected part of an innovation and $\sigma_{t,i}v_i$ is the unexpected part. However, since i has a choice to employ or not in its research some *a priori* unexpected research path, it is irrational for i to contact its research mainly using $\sigma_{t,i}v_i$. This is because, as the above intuition implies, $\sigma_{t,i}v_i$ can attain negative values as well. Subsequently, if i chooses to follow a high σ strategy it might end up with an innovation $\Delta A_{t,i}$ which is less than expected. On account of the above, the expected innovation should be,

$$E\Delta A_{t,i} = \gamma + \sigma_{t,i}M_i \tag{3.19}$$

where $M_i = \mu_i - \gamma$ and E is the expectations operator. Since $\mu_i \geq 0$, $\gamma > 0$ and $\sigma_{t,i} \in (0,1)$, $E\Delta A_{t,i}$ should be greater than zero.

In the light of the above, if i has a μ_i that is equal to zero then i's expected innovation is $E\Delta A_{t,i} = (1 - \sigma_{t,i})\gamma$. Contrary to that, if i has the capacity to follow a research strategy where $\sigma > 0$ and, on average, derive some positive innovation, then it will have a μ_i that is greater than zero. Thus, i is expected to create an innovation that is greater than $(1-\sigma_{t,i})\gamma$.[84]

Since v_i can attain negative values it is possible for $\Delta A_{t,i}$ to be less than zero. If this turns out to be true, it implies that research has followed the wrong path. In this case, the firm will make use of the technology that it has developed up to tournament $t-1$.[85] Similar to chapter two, an example of a technology that did not generate the expected results would be the High Definition TV (HDTV). In the late 1980's this was a promising European TV standard that turned out to be costly and outdated (when compared to the USA TV technology of its time).[86]

Accounting for the above discussion, one should ask the following question. Is there any reason to believe that μ_i can be greater than γ (the set rate of technological change)? One can think of the following two situations where the above is plausible. If the firm has advanced fundamental research capabilities, which allows it to successfully use new and not well understood techniques, or if the technology is a new technological paradigm. In the latter case γ must be small because there is no prior learning and no prior experience in the form of knowledge spillovers. For example, computers in the early 1950's were a brand new technological paradigm on which the use of prior art had limited effects. Therefore,

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[84] In view of the Bell Laboratories example, Bell was employing some of the best US scientists (and some later Nobel price winners) and made a lot of effort to diffuse the knowledge created by US universities in its research program. Thus, one can allow Bell to have a μ that is higher than the μ of a firm for which the above do not apply.

[85] Hence, equation (3.18) must be re-expressed as, $A_{t,j} = A_{t-1,j} + \max\{0, \Delta A_{t,j}, \lambda \Delta A_{t,i}\}$.

[86] In 1991 the European Commission, in an initiative that was backed up by various satellite interests, proposed an expensive plan, which was worth of 850 million Euro, to support the HDTV standard plan. There was considerable debate in the Council about the budget, but finally the issue was dropped, with the justification being that a more advanced technology was already available in the US. For a detailed discussion of the HDTV project see Braithwaite and Drahos (2000).

one could not base his research on already established research paths. On the contrary, one had to experiment with new tools and ideas on which there was limited prior knowledge and understanding.

I have up to now created two quality ladders that correspond to two different competing firms. As it will become apparent in the following section, competition in this framework will depend on the distance that separates the technologies created by the two competitors. If the two quality ladders are of dissimilar magnitude, since there is a clearly defined leader (the firm with the higher A), there is limited competition. Symmetrically, if the two quality ladders are of similar magnitude there exists competition. This is because i, j are close enough to be able to leapfrog each other. Accordingly, the closer i, j get the easier it will be for i, j to leapfrog each other. In this context, one way of increasing competition is to increase λ, making it easier for the follower to re-innovate around the leader's technology. This way, the follower will increase its technology getting closer to the leader.

3.4 Solving the model

Every firm has an expected probability $Ep_{t,i}$ of winning tournament t, where $Ep_{t,i} \in (0,\ 1)$. Since this section will concentrate on a static problem the subscript t will be omitted. In addition, I will assume that Ep_i does not become either one or zero, thereby the duopolistic structure of the tournament never deteriorates to a monopoly.[87] Ep_i expresses the expected probability that i has of creating a technology that is greater than the one created by j, i.e. $Ep_i\,(A_i > A_j)$. This line of reasoning suggests that the greater EA_i is, the

[87] This should always be true if $\Delta A_{t=0,i} \sim \Delta A_{t=0,j}$.

more likely it will be for i to win the tournament. On the contrary, if j has a large EA_j, it will decrease the chances that i has of winning. Therefore, for $Ep_i\,(A_i,A_j)$,

$$\frac{\partial Ep_i}{\partial EA_i} > 0, \frac{\partial Ep_i}{\partial EA_j} < 0. \tag{3.20}$$

where for simplicity I am making the assumption that all cross derivatives and second order derivatives are small enough to be effectively considered as zero. Nevertheless, one can suggest that $\frac{\partial^2 Ep_i}{\partial EA_i^2} < 0$, which implies that, as EA_i increases, probability Ep_i will increase with a diminishing rate of increase. This could be the result of knowledge spillovers. Specifically, having allowed for knowledge spillovers, the greater EA_i is the more the knowledge spillovers available to j. This means that as EA_i increases it will increase γ, leading to an increase in EA_j, which should negatively affect Ep_i. However, as I noted in the previous section, Pakes and Schankerman (1979) find that spillovers diffuse slowly. Therefore, one can allow for $\frac{\partial^2 Ep_i}{\partial EA_i^2} \rightarrow 0$.

The consumption good is produced in the following fashion,

$$y = A_i x^a \; a \in (0,1) \tag{3.21}$$

where the subscript i in y and x has been omitted because there is always only one winner. Similar to Aghion and Howitt (1992), the producer's profits are,

$$\pi_i = aA_i x^a - wx - cx$$

where $c > 0$ is the production cost per unit x of the intermediate input (which is produced by x production workers all equipped with one unit of labour). Production workers x

receive a set fraction of the profits $\epsilon\pi_i$, i.e. $w = \frac{\epsilon\pi_i}{x}$. Thus,

$$\pi_i = \frac{aA_i x^a - cx}{1+\epsilon} \tag{3.22}$$

The winner will maximize its profits π_i subject to x. This maximization problem has the following FOC,

$$x = \left(\frac{a^2 A_i}{c}\right)^{\frac{1}{1-a}} \tag{3.23}$$

Since the firm must choose its σ at the beginning of the tournament, before its innovation is materialized, firms solve the following problem,

$$\max_{\sigma_i} Ep_i\left(A_i, A_j\right) E\pi_i$$

Using equations (3.22)-(3.23) the FOC from this maximization is given by the following implicit function,

$$F\left(\sigma_i\right) = \frac{\partial Ep_i}{\partial \sigma_i} E\pi_i + Ep_i \frac{\partial E\pi_i}{\partial \sigma_i} = 0 \tag{3.24}$$

Bearing in mind that $\frac{\partial Ep_i}{\partial EA_j} < 0$, using the implicit function theorem on equation (3.24), the following condition is derived,

$$\frac{\partial \sigma_i}{\partial EA_j} = -\frac{\frac{\partial Ep_i}{\partial EA_j}}{M_i\left(2\frac{\partial Ep_i}{\partial EA_i} + \frac{\alpha}{1-a}\frac{Ep_i}{EA_i}\right)} \tag{3.25}$$

In equation (3.25), $\frac{\partial \sigma_i}{\partial EA_j}$ is always greater than zero if $M_i > 0$, which suggests that, if $\mu_i > \gamma$, the greater the expected technology of firm j is the greater the choice of σ_i for firm i will be.

Overall, the above discussion allows one to concentrate on the following question, how will the leader respond to an increase in A_j? As it turns out, if $\mu_i > \gamma$ any increase in EA_j should *ceteris paribus* lead i to respond by adopting a greater σ_i. In a similar fashion, if $\mu_j > \gamma$, when the follower j faces the leader's higher technology, it must also adopt a greater σ_j in its innovation process; because $\frac{\partial \sigma_j}{\partial EA_i} > 0$. The above intuition implies that if between two tournaments there is an increase in λ, which leads to more competition, then there will be an increase in σ. As a result, considering that $E\Delta A_i = \gamma + \sigma_i (\mu_i - \gamma)$, if $\mu_i > \gamma$, increases in λ lead to a greater σ, a greater expected innovation and a greater expected technology EA_i.

3.5 The optimal patent protection

The objective of a central planner is to maximize expected output y with respect to λ. Accordingly, the central planner's maximization problem is,

$$\max_{\lambda} Ey = EA_i x_t^a$$

Accounting for equations (3.19), (3.23) and (3.25), the FOC is,

$$Q(\lambda) = \frac{\frac{\partial Ep_i}{\partial EA_j} E\Delta A_i \left(\frac{a^2 EA_i}{c}\right)^{\frac{\alpha}{1-a}} \left(1 + \frac{1}{1-a}\frac{c}{aEA_i}\right)}{2\frac{\partial Ep_i}{\partial EA_i} + \frac{\alpha}{1-a}\frac{Ep_i}{EA_i}} = 0 \tag{3.26}$$

Having at hand a suitable function for p one can solve the above implicit function for λ. Nevertheless, even in the absence of such a function an important result can be reached. Specifically, using the implicit function theorem on equation (3.26),

$$\frac{\partial \lambda}{\partial M_i} = \frac{\frac{1-a}{a}\sigma_i EA_i \left(2\frac{\partial Ep_i}{\partial EA_i} + \frac{\alpha}{1-a}\frac{Ep_i}{EA_i}\right)}{\frac{\partial Ep_i}{\partial EA_j} E\Delta A_i} \left(1 + \frac{\frac{1}{(1-a)}\frac{E\Delta A_i c^2}{aEA_i^2}}{a(1-a)EA_i + c}\right)$$

Since $\frac{\partial Ep_i}{\partial EA_j} < 0$, this function is always less than zero if $\mu_i > \gamma$.

What does the above inequality imply in terms of optimal patent breadth? Bearing in mind that a greater λ implies that more re-innovation can take place, the above result suggest that if the firm has advanced research capabilities allowing $\mu_i >> \gamma$ (or alternatively, if the technology involved is that of a new technological paradigm) it requires greater patent protection compared to a firm for which $\mu_i > \gamma$. Notwithstanding the above, and in the context of the economy as a whole, μ_i is an institutional parameter expressing not only the ability of i to foster fundamental research, but the ability of the economy in which the firm operates as well. This is because i is the tournament's winner. Thus, by definition μ_i represents the whole economy, because i is the only firm producing (one can think of i as a national champion). Using such an interpretation for μ_i, one can suggest that different economies may require a different intellectual property protection policies because their ability to foster fundamental research varies. In other words, different national systems of innovation (NSIs)[88] may require different intellectual property protection policies.

Against this background, an example of the approach that different NSIs follow when innovating may be educational. Accordingly, if one is to make a general comparison between the US NSI and the European one,[89] eventhough there is no doubt that each NSI has its strong points,[90] there is a general consensus that the US system is better suited to promote fundamental research. As Goyer (2001) notes, *'By contrast* [to the German system of innovation], *the American system.... is well suited for radical innovation, which requires the introduction of radical innovative design and rapid development based on pure scien-*

88 There is a growing literature that examines the differences between various NSIs, see Nelson (1992), Mowery and Rosenberg, (1998). This literature suggests that different NSIs employ state, university, laboratory and firm research in different ways. In fact, as Soskice (1999) notes, the most important elements of this framework are, the corporate governance system, the financial system, the industrial relations/worker training system, the education system, the organization of employer associations and the relations among firms. How countries employ the above elements affects their ability to innovate and the type of innovation they can produce.

89 Which is broadly comprised by three independent and different national systems, the French, the German and the UK one.

90 In the US the firm in cooperation with universities is central to research, while in European NSIs the state has a larger role to play

tific research'. This difference is highlighted in the different research paths US and German firms follow in the field of biotechnology. Specifically, German firms follow a low-risk innovation strategy, concentrating on proteins whose therapeutic properties are already well established. In contrast, the US firms, as Henderson *et al.* (1999) note, have used biotechnology as a search technique and their primary focus is on the discovery of small molecules designed to increase the productivity of synthetic drugs. Therefore, the above framework suggests that Germany may find it optimal to allow for a less strict patent protection in order to stimulate (through greater competition) its firms to produce greater innovations and greater output.

3.6 Conclusions

In the 1990s a large part of the intellectual property literature concentrated on the trade-off between patent breadth and patent length. The main argument used was that greater patent breadth gives the innovator more protection from imitators (which acts as an incentive to innovate) at the cost of offering monopolistic rights to the innovator. However, as Scotchmer (1991) noted, if innovation is sequential, as it frequently is, then the patent holder can block all other innovators from employing his patent in the future. Subsequently, unless cross-licensed, patents can decrease competition between innovators (competition for the next innovation), allowing only the patent holder to use the latest technology in developing a better one.

Working within the context of a patent race, this model concentrates on patent-induced lack of competition when innovation is sequential. The view that this model takes is that the resulting lack of competition can be detrimental for innovation, because it leads innovators to rest on their laurels and abstain from pursuing innovation strategies that can potentially lead to radical innovations.

Specifically, there is a large literature that points to the excessive risk that competitive tournaments can lead to.[91] In the context of a patent race, bearing in mind that innovation is a twofold process, which (in general) relies on the use of both prior art and experimentation, risky experiments can potentially lead to radical innovations, such as the transistor, or to dead end results. The success, or not, of experiments largely rests on the quality of research. One should expect that innovators that operate on the edge of the technology frontier, have high quality researchers and allow for links with universities and laboratories, must be better equipped to successfully handle risky experiments, compared with ones that don't. Such innovators can benefit from the risk involved in competitive patent races and through successful experimentation can create radical innovations.

Accounting for the above, this chapter's main result is that, for economies with an advanced ability to perform research, or in the presence of a new technological paradigm, there is a positive relationship between the economy's ability to innovate and the optimal patent protection, the one that maximizes production.

Appendix one

In the Aghion and Howitt (1992) model the economy is populated by a continuous mass L of individuals with linear preferences. Output of the consumption good depends on an intermediate input x (the intermediate good accounts for technological change) accord-

[91] See Harris and Vickers (1987), as well as Dasgupta and Stiglitz (1980).

ing to,

$$y = Ax^{\alpha},\ \alpha \in (0, 1)$$

while each innovation raises the technology parameter A by the constant factor γ. In this economy there is no population growth, and workers can only use their labour either in research (research workers are denoted by n), or in production. Production workers are endowed with one unit of labour, hence x units of the intermediate input require x workers. This suggests that

$$L = x + n$$

In this economy innovations arrive with a Poisson arrival rate of $\lambda n > 0$, where λ indicates the productivity of research. The firm that succeeds in innovating monopolises the intermediate sector market until replaced by the next innovator.

Portraying the research sector as in the patent-race literature, the amount of labour devoted to research is determined by the following arbitrage condition,

$$w_t = \lambda V_{t+1}$$

where t indicates the indexing of innovations and w is the wage, which, due to full labour mobility, is equal for both research workers n and production workers x. Furthermore, the value of an innovation V_{t+1} is determined by the following asset equation,

$$rV_{t+1} = \pi_{t+1} - \lambda n_{t+1} V_{t+1}$$

where π_{t+1} indicates the profit flow of the $t + 1$ monopolist.

Noting that production takes place in a perfectly competitive environment (contrasting research), the t^{th} incumbent innovator will determine π_t and x_t by solving,

$$\pi_t = \max_x \left[p_t(x_t)x_t - w_t x_t\right]$$

where $p_t(x_t)$ is the price at which the t^{th} incumbent innovator can sell the flow x of the intermediate input to the final goods sector. The FOC is,

$$x_t = \left(\frac{\alpha^2}{w_t/A_t}\right)^{1/(1-\alpha)}$$

From the above one can determine the productivity adjusted wage $\omega_t = w_t/A_t$ as,

$$\omega_t = \lambda\frac{\gamma\pi\left(\omega_{t+1}\right)}{r+\lambda n_{t+1}}$$

The model's solution is characterised by the above equation, as well as the labour market clearing equation,

$$L = x_t + n_t$$

while, in the steady state, the average growth rate of the economy is given by,

$$g = \lambda\hat{n}\ln\gamma$$

where $\hat{n}$ indicates the number of research workers in the steady state.

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Chapter 4
Optimal Patent Protection When Innovation is Sequential

4.1 Introduction

In recent years we have witnessed an increase in patent protection in the US. This increase has been manifested through the formation of the Court of Appeals of the Federal Circuit (Federal Courts Improvements Act) in 1982, the introduction of the Patent and Trademark Laws Amendment (Bayh-Dole) in 1980, the increase in patent length form 17 to 20 years, and the introduction of patent protection for previously unpatentable works, such as software and business methods. This increase is not restricted to the US and similar developments have been introduced worldwide through WIPO and TRIPS. It seems that strong patent protection is a modern day *'mantra'*, which postulates that it offers greater incentives to innovators, increasing overall economic performance.

Various scholars have criticized the above view. For example, Cohen, Nelson and Walsh (2000) find that despite the fact that firms are taking out many more patents, managers do not perceive patents to be any more effective. This view coincides with evidence from Hall and Ziedonis (2001), who note that for technology sectors (such as microprocessors) where innovators are interlocked in using each other's technology, patents act as a *'secondary defense'* in protecting innovation and firms cross-license their patents to rival firms. Such critical views are not restricted to the empirical literature. From a theoretical perspective, O'Donoghue, Scotchmer and Thisse (1998) also cast doubt on the above view, noting that true as it may be that a patent rewards the present innovator, it nevertheless hinders all future re-innovation.

The importance of this issue is further highlighted by recent evidence from Lerner (2004), who in an international analysis of the relationship between patent strength and innovation, examines 177 policy shifts in 60 countries over 150 years and finds some support for an inverse U relationship. On the basis of the above, the aim of this chapter is to examine whether patent protection promotes innovation and output growth.

While accounting for the view that patents reward the innovator, acting as stimuli, this chapter will also concentrate on two additional ways through which greater patent protection can affect innovation. The first one, similar to chapter 3, is based on the idea that the more one feels a competitor's breath behind his back the more he is forced to run. The second way is channeled through knowledge spillovers. Specifically, an increase in patent protection will make it harder for other innovators to bypass a patent. Lerner (1995), working on biotechnology firms, finds that this difficulty may force some innovators to abstain from innovating in this particular sector. Such a reduction in innovative effort may lead to a drop in knowledge spillovers. Therefore, in a broad way, the model concentrates on the merits of duplication, acknowledging that if many innovators work on the same technology, even though some of their work is mere duplication, they create knowledge spillovers that can potentially affect all innovators.

The argument of this chapter will be substantiated through a static tournament model where many innovators race to create the greatest technology. The introduction of the tournament allows one to specifically model competition between innovators. In the second part of this chapter, in order to study the effect that patent protection has on output growth, this tournament model will be extended to include, similar to Loury (1979), a simple dynamic endogenous growth framework based on Aghion and Howitt (1992). It should be noted that the growth model is not essential to the chapter's results. In fact, all the important comparative statics will be proved within the static framework before I re-introduce them to the dynamic model. Nonetheless, the latter model allows one to concentrate on the following question, what is the optimal patent protection, the one that maximizes output growth? Accounting for the above, running a numerical simulation on the latter model I find that there is an inverse U relationship between patent protection and output growth.

The notion of patent protection used refers to patent breadth, where patent breadth will be defined as the re-innovation that is allowed to take place within the boundaries of legal protection. In addition, patent breadth will be a choice variable for the central planner, who is supposed to act on behalf of the courts and the PTO, and whose objective is to maximize output growth. As section 4.3 explains, in broad terms the definition of patent breadth suggested here is similar to Matutes, Regibeau and Rockett (1996). Overall, in broad terms, one can interpret patent breadth as either the number of patent claims the PTO allows for, or how strong the courts' attitude towards infringement is. Hence, the model will not be discussing the time dimension of patents. This is due to the already extended discussion that this issue has received during the 90s, albeit in the context of models whose objective was to minimize the deadweight loss that is associated with patents; see Gallini (2002) for a literature review.

The model is not without its drawbacks. For example, in order to clarify the analysis, I have laboured under the assumption that there is no cross licensing, and I have limited any strategic interaction between the innovators, allowing it to be present only when tournaments become highly competitive. In addition, I have assumed that there is no cost attached to risk. In reality this is not true. However, as I argue, when a tournament becomes highly competitive innovators choose to follow high-risk strategies. Therefore, if there is an increasing cost attached on risk, when the tournament becomes more competitive it will decrease the profits of some participants leading them to abstain from taking part in the tournament. Such a decrease in the number of innovators will decrease knowledge spillovers adversely affecting innovation. Overall, attaching an increasing cost on risk imposes on the model an additional effect on knowledge spillovers, one that is similar to the one that I have already described in a previous paragraph. Subsequently, in order to avoid any duplication and make the model tractable I abstain from attaching an increasing cost on risk

The outline of this chapter is the following. Section 4.2 introduces the tournament and the way technology is generated. Section 4.3 displays the model's main properties. Section 4.4 extents the model by introducing a simple growth framework, while section 4.5 contains the simulation and it is followed by the conclusions.

4.2 Assumptions

In what follows this chapter will focus on industries such as biotechnology and pharmaceuticals. These are industries where patent protection is a successful way of protecting one's innovation, and, accordingly, patents are essential to firms. In addition, these industries face a lot of obsolescence, making the latest innovation by far the most important and useful one, both in production and as a base for further research.

I here frequently use the terms innovation, technology and neck and neck markets. To avoid confusion, I will provide a definition of these terms. For the purpose of this chapter, technology A is the sum of many sequential individual innovations. Innovations, in turn, are defined as marketable technological advances, which are not obvious beforehand to someone skilled in the prior art. In this model, an innovation ΔA, will be the result of the winning innovator's research between tournaments. As a neck and neck (for simplicity N-N) market/tournament, I define a market in which the technologies of the innovators are almost of identical magnitude. Therefore, a N-N market is a highly competitive one, because the innovators are positioned closely to each other.

Many heterogeneous potential-innovators participate in a series of tournaments in which all the participants have full information about each other. Hence there are no trade secrets and an innovator has no option but to patent his innovation in order to protect it from imitators.[92] Innovators are assumed to be risk-neutral individuals, and their role is to form the idea that will become an innovation. In order to participate in tournament t (where t denotes the ordering of periods and tournaments), innovators must incur a sunk cost C which represents the cost of building a laboratory and the effort to diffuse in one's research the latest findings by universities etc. The objective of a tournament is to build a

[92] In the absence of trade secrets the innovator must patent his ideas even when he fails to win the tournament. Otherwise, he will allow other innovators to free ride on his technology making it harder for him to win future tournaments, because he will have to compete with many other innovators who have the same technology.

technology of the greatest possible magnitude. Hence, when a tournament ends, the winner will be the innovator who builds such a technology. Each tournament will lead to only one technology, which will be employed in the production of a consumption good.

The technological advances that the remaining innovators achieved during the tournament will be treated as inventions. These inventions can be used as a base for one's future research but they will not find any marketable application, unless the innovator succeeds in winning a tournament. If an innovator chooses not to take part in a tournament he stops his research.

In order to innovate the innovator needs to employ research workers n. These workers, who are assumed to be homogeneous, will receive, similar to Jones (2001), a fixed percentage ϵ of the revenues that the innovation generates. The remaining $1-\epsilon$ will be the innovator's payment. The revenues that an innovation ΔA_t generates are π_t. For simplicity, I will assume that π_t is a positive function of ΔA_t, and that n_t depends positively on the expected revenues from ΔA_t. In the first part of this chapter I will not offer any microeconomics structure backing these two assumptions. This will be included in the second part of the chapter.

If one was to introduce an endogenous labour market condition determining how profits are divided between the innovator and the n research workers, this must be directly or indirectly affected by the model's main variable of interest, namely patent breadth. However, there seems to be (as far as I know) no empirical evidence connecting the labour market to patent breadth. An alternative assumption would be to allow (as Jones (2001) effectively does) the innovator to appropriate a greater part of profits as patent breadth increases. It should be stressed that working under such an assumption does not alter the chapter's results and final formulas.

Innovators innovate sequentially.[93] Assuming that no cross-licencing takes place, the innovation that the innovator builds in the course of a tournament adds to the technology that he had developed in the previous tournament,[94] (i.e. $A_t = \sum_0^t \Delta A_t$), where patents are assumed to last for two periods. If there is no (or limited) patent protection innovators will manage to re-innovate around the winner's patent (re-innovation implies the legal development of an innovation with similar or identical capabilities). If there is patent protection, depending on how much re-innovating is allowed, the innovators will use either their own innovation, or the one that they built by re-innovating (whichever one is of larger magnitude). At the same time, since patents reveal how an innovation functions this information will spillover to all innovators.

For example, if an innovator works on catalysts, any information included in all other innovators' patents (who also work on catalysts), assists the innovator in his research effort. This could be because the innovator becomes aware of the research path that the other innovators have followed and what type of research should be avoided, or simply because the innovator has knowledge of what all the other innovators are currently working on. Nevertheless, this knowledge cannot be translated into an innovation because it is protected by a patent. Therefore, even though the innovator knows and understands the latest catalyst

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93 There is a considerable literature which explores the time technology generation process in situations where the R&D investment of the firm endogenously shapes technology. For a review see Baldwin and Scott (1987).

94 This assumption implies that the tournament will not be a memoryless race, unlike the tournament models of Dasgupta and Stiglitz (1980), and Reinganum (1984).

technology, he cannot use it without licence. If he wants to use it he must either pay royalties for a licence (this does not happen in this model because no cross-licencing is allowed), or attempt to re-innovate around the patent. This re-innovation will take place during the next tournament.

In the light of the above, (denoting the technology of the winning innovator j, during tournament t as $A_{t,j}$ and his innovation as $\Delta A_{t,j}$), innovator i (a follower) will be able to advance his technology $A_{t,i}$ by $\max\{\Delta A_{t,i}, \lambda\Delta A_{t,j}\}$, where $\lambda \in (0,1)$ indicates how much re-innovating around $\Delta A_{t,j}$ innovator i can do.[95] In this context, λ can be considered as patent breadth. For example, if λ is close to zero then i cannot re-innovate around the innovation of innovator j. On the contrary, if λ is close to one then i can re-innovate around, which suggests that i will end up with an innovation that is of equal size to that of the winner. Accounting for the above, the technology of innovator j is,

$$A_{t,j} = A_{t-1,j} + \max\{\Delta A_{t,i}, \lambda\Delta A_{t,j}\} \tag{4.27}$$

In this framework, one way of increasing tournament-based competition is to increase λ, making it easier for the followers to re-innovate around the leader's technology. This way, the followers will increase their technology getting closer to the leader. However, since $\lambda \neq 1$ and patent length is two periods long *ceteris paribus* an increase in λ will not create a tournament where all innovators have identical technologies. Thus, the tournament is unlikely to become perfectly competitive. Henceforth, λ will be considered a policy instrument used by the central planner.[96]

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[95] λ cannot be one because in reality there exists tacit knowledge, which does not allow full re-innovation to take place. In addition, it is practically impossible to allow no re-innovation to take place. Therefore, $\lambda > 0$.

[96] In reality, even though (in the US) patent breadth is decided by the PTO, the courts and Congress, it is up

The time-line of the model is the following. Competing innovators employ research workers and start their research while participating in a tournament. At the beginning of the tournament innovators make all the irreversible decisions regarding innovation, choosing what type of innovation path to follow. Production will take place immediately before the next tournament commences.

4.2.1 Technology

The purpose of this section is to study how technology is built. I will assume that any discovery is the combined result of four factors, prior art, luck, research workers and knowledge spillovers. Prior art, in the form of the already made technological discovery $\Delta A_{t-1,j}$, is the building block on which one can base his research. Without prior art one must start from scratch. In addition to prior art, research workers $n_{t,j}$ must be used because they are the ones who create the innovation. In the absence of the above inputs, the resulting innovation will be dependent on luck and on the risk that the innovator is willing to employ in his research.

Furthermore, as Segerstrom (1998) argues, the more advanced (complicated) technology is the harder it is to innovate. Therefore, prior art can also affect innovation in a negative way. However, as Panagopoulos (2003) notes, an increase in knowledge spillovers $s_{t,j}$ increases the innovator's ability to cope with complicated prior art, where in this framework $s_{t,j}$ express the collective experience that all the tournament participants (absent j) generate by patenting their innovations. Subsequently, the greater the knowledge spillovers

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to the firm to seek litigation if it finds out that rivals have used its technology.

that an innovator manages to attain the less the difficulty that he will face during the innovation process.

In what follows, I will introduce a technology generation function, which describes how technological discoveries ΔA are created. Specifically, every innovator j uses the following technology generation function,

$$\begin{aligned} \Delta A_{t,j} &= \Delta A_{t-1,j}^{\zeta} n_{t,j}^{\xi} - \frac{c\Delta A_{t-1,j}}{s_{t-1,j}} + \sigma_{t,j} z_{t,j} \\ c &> 0, \sigma_{t,j} \in [0,1] \end{aligned} \tag{4.28}$$

to develop a series of innovations $\Delta A_{t,j}$ that will allow him to create a technology and participate in the tournament. The initial condition for equation (4.28) is $\Delta A_0 \geq 0$. To avoid multiple winners in the first tournament, I will make the assumption that only one innovator has the initial idea to generate ΔA_0.

In equation (4.28), $\Delta A_{t-1,j}^{\zeta} n_{t,j}^{\xi}$ expresses an innovation as the combined result of prior art $\Delta A_{t-1,j}$ and research workers $n_{t,j}$. In addition, $\frac{c\Delta A_{t-1,j}}{s_{t-1,j}}$ describes the increase in difficulty that an innovator faces when he tries to create increasingly larger innovations.

Lastly, $z_{t,j}$, which is distributed with a mean 0, is a term that can produce irregular steps of magnitude $\sigma_{t,j} z_{t,j}$. These steps can vary both upward and downward and are *a priori* unforeseen. Because of that, $\sigma_{t,j} z_{t,j}$ is used to represent luck. Moreover, since the greater $\sigma_{t,j}$ is, the greater the possible range of $\sigma_{t,j} z_{t,j}$ becomes, one can use $\sigma_{t,j}$ to represent how risky a project is.[97] Since $\sigma_{t,j} z_{t,j}$ can attain negative values it is possible for

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[97] In general one should expect that research paths that involve greater risk, if successful, should lead to innovations of greater magnitude (when compared with less risky research paths). For a discussion on the uncertainty surrounding innovation see, Rosenberg (1996).

$\Delta A_{t,j}$ to be less than zero.[98] If this turns out to be true, it implies that research has followed the wrong path. In this case, the innovator will not make use of $\Delta A_{t,j}$.[99] An example of a technology that did not generate the expected results, similar to chapter 3, would be the High Definition TV.

In equation (4.28), $\Delta A_{t,j}$ is the result of the latest prior art $\Delta A_{t-1,j}$. True as it may be that such an assumption accords well with the way research is carried out in industries such as biotechnology and pharmaceuticals (because of the high obsolescence rate that they face), one can also provide an alternative/complementary intuition. Accordingly, bearing in mind that patents last for 2 periods, A_{t-2} must be common and well understood knowledge. Subsequently, considering that research workers are homogeneous, any research that uses A_{t-2} as a base for developing new knowledge should produce similar results among all innovators. Therefore, in addition to the $\Delta A_{t,j}$ that is generated via $\Delta A_{t-1,j}$, through equation (4.28), one should expect innovators to create a common ΔA based on A_{t-2}. To avoid any duplication, bearing in mind that luck does not depend on A, it is only the latest increment $\Delta A_{t,j}$ (the one produced through equation (4.28)) that is affected by luck. Accounting for the above, considering that the model will concentrate on the differences between the technologies created by the innovators, common terms will always cancel out allowing one to focus only on how the latest prior art effects the creation of an innovation.

In order for an innovator to win the tournament he must create a technology that is greater than the one created by all other innovators. Accordingly, I will endow each

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98 By contrast, since z has a zero mean and $\Delta A_{t-1,i} = \max\{\Delta A_{t-1,i}, \lambda\Delta A_{t-1,j}\}$, where $\lambda \in (0,1)$, the $E\Delta A_{t,i}$ that is given by equation (4.28) is always greater than zero.

99 Accounting for this negative innovation, one should rewrite equation (4.27) as, $A_{t,j} = A_{t-1,j} + \max\{0, \Delta A_{t,i}, \lambda\Delta$

innovator j with an expected probability $Ep_{t,j}$ of winning the tournament. I will allow $Ep_{t,j}(A_{t,j}, A_{t,i}) \in [0,1]$, $i \neq j$, $i \in [1, v_t - j]$ to be a function of the technology that j is expected to create, as well as of the technology that all other innovators $i \neq j$ are expected to create. In this context, one should expect that, $\frac{\partial Ep_{t,j}}{\partial EA_{t,j}} > 0$, $\frac{\partial Ep_{t,j}}{\partial EA_{t,i}} < 0$. The latter inequalities imply that the greater one's expected technology is the greater his chances of wining the tournament are. Moreover, the greater the expected technology of one's competitors is, the lower his chances of winning the tournament are. Furthermore, I will allow for all cross derivatives to be small enough to effectively be considered as zero.[100]

Intuitive as $Ep_{t,j}(A_{t,j}, A_{t,i})$ may be it is always preferable to provide some mathematical intuition and an exact mathematical function that backs such an assumption. As Appendix one shows, this can be done by working in continuous time, viewing equation (4.28) as an Ito's stochastic differential equation. This being the case, using the *Kolmogorov's backward equation* one can derive the probability that j has of creating a technology that is greater than $i's$. The main drawback of this approach, even though it leads to similar results as the rest of the chapter, is its increased mathematical difficulty, and its reliance on graphical interpretations.

4.2.2 Finding the number of tournament participants

In this section, the innovators' motive to participate in the tournament is explored. Accordingly, I will try to determine which innovators find it profitable to enter the tournament (thus I will try to determine v). In order to find who enters, I will examine the innovator's

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100 Even though this assumption simplifies the results the model's proofs will not change if one allows the cross derivatives to be different than zero.

value of entering the current tournament. In doing so, I will treat the decision to innovate as an investment decision. In this case, the investment will have a limited horizon of one period and it must commence at the beginning of the tournament. Thereby, in a fashion similar to Dixit and Pindyck (1994), I will form the innovator's expected option value function to investing.[101] One should expect that only innovators who have a positive option value will decide to take part in the tournament. In this context, the expected option value of an innovator j is,

$$F_{t,j} = (1 - \epsilon)\, Ep_{t,j}\pi_{t,j} - C \tag{4.29}$$

In equation (4.29), $F_{t,j}$ is the expected option value to the investment of innovator j (the option value of entering the tournament), C is the sunk cost of entry and $(1 - \epsilon)\,\pi_{t,j}$ are the profits that the winner gets from employing his technology in the production of a consumption good (thus $(1 - \epsilon)\, Ep_{t,j}\pi_{t,j}$ are the expected revenues from the innovation).

Only innovators who have an $F_{t,j} > 0$ will take part in the tournament. Subsequently, since the greater $Ep_{t,j}\,(A_{t,j}, A_{t,i})$ is the higher $(1 - \epsilon)\, Ep_{t,j}\pi_{t,j}$ is, innovators who have a higher probability of winning the tournament are more likely to participate in the tournament, because for these innovators $(1 - \epsilon)\, Ep_{t,j}\pi_{t,j} > C$ and $F_{t,j} > 0$. The number v_t of the innovators who have a positive $F_{t,j}$ is of interest, since it determines the magnitude of the knowledge spillovers $s_{t,j}$; increases in v_t increase the $s_{t,j}$ available to the innovators, leading to a greater $\Delta A_{t,j}$.

101 See also, Grenadier (1996), Kulatilaka and Perotti (1998), Lambrecht and Perraudin (1997).

4.3 Some comparative statics based on patent breadth

In this section I will compare the effects that different types of tournaments can have on innovation. The main difference between tournaments will be on how close the innovators are positioned to each other. As I mentioned in section 4.2, one can vary the distance between innovators by changing the patent breadth λ allowing innovators to re-innovate more. Thereby, the question that this section poses is the following, what impact will an increase in λ have on innovation?

To this question the model indicates that patent breadth can affect innovation in three different ways. The first one indicates that an increase in tournament competition (caused by an increase in λ) can be detrimental for innovation. Hence, a tournament where only one (or a few) innovators can win is preferable to a tournament in which all innovators have equal chances. Specifically, as λ increases and innovators get closer (increasing $A_{t,i}$), the expected probability $Ep_{t,j}\left(A_{t,j}, A_{t,i}\right)$ that innovator j has of winning the tournament is reduced, reducing the expected revenues from the innovation $Ep_{t,j}E\pi_{t,j}$. Such a reduction in expected revenues should lead to a lower $n_{t,j}$ and a drop in $\Delta A_{t,j}$.

The above argument describes how the leading innovator will respond as λ increases. The second way that a change in λ can affect innovation reverses the above result, examining how the followers will respond. The rationale behind this rests on the increase in knowledge spillovers that one should expect if more innovators participate in the tournament. Specifically, noting that the tournament never becomes perfectly competitive (since $\lambda \neq 1$ and patent length is two periods long), any increase in λ increases the technologies of the lagging innovators. Therefore, *ceteris paribus*, such an increase in technology should lead to an increase in the lagging innovators' probability to win the tournament, making it profitable for more lagging innovators to enter the tournament, increasing knowledge spillovers, leading to a greater innovation.

Specifically, section 2.1 introduced for each innovator an expected probability of success $Ep_{t,j}\left(A_{t,j}, A_{t,i}\right)$. This probability depends on his $EA_{t,j}$, as well as on the $EA_{t,i}$ of all the other innovators. If an innovator has a greater $EA_{t,j}$ (compared to the other innovators), he increases his expected probability of winning the tournament, while decreasing that of the other innovators. However, a drop in the expected probability of winning the tournament (caused by a decrease in λ , which brings the innovators further apart) leads to a reduction in the $F_{t,j}$, see equation (4.29), forcing some innovators to abstain from entering the tournament, reducing v_t and lowering knowledge spillovers. Bearing in mind that $\Delta A_{t,j} = \Delta A^{\zeta}_{t-1,j} n^{\xi}_{t,j} - \frac{c\Delta A_{t-1,j}}{s_{t-1,j}} + \sigma_{t,j} z_{t,j}$, if $s_{t,j}$ decreases, there should be a decrease in $\Delta A_{t+1,j}$. Flipping the argument, any increase in competition, which leads the followers to increase their $EA_{t,i}$, should *ceteris paribus* increase the followers' $Ep_{t,i}$. A greater $Ep_{t,i}$ implies an increase in the followers' $F_{t,i}$, which suggest that more innovators will enter the tournament.

The last way through which λ can affect innovation is channeled though risk σ. Specifically, if the central planner is to increase λ allowing many innovators to get close enough as to form a N-N tournament, these innovators will only have one option if they want to win, namely to increase their risk. This is because in N-N tournaments innovators are positioned close enough to have a similar A_{t-1} and a similar probability of winning. Therefore, an innovator cannot win based on his technology.

In detail, innovators maximize expected profits $(1-\epsilon)\, Ep_{t,j} E\pi_{t,j}$ with respect to $\sigma_{t,j}$. Since they are not aware of future realization of z they can only solve a static problem. Furthermore, z can only become evident once the tournament commences, while σ must be chosen at the beginning of the tournament. However, if a tournament is a N-N one it is impossible for the winner to have a negative realization of z, because he would find it impossible to win and his place would be taken by an innovator with a positive z. The only way possible to have a negative z and still win is if all the other contestants also have a negative z, but this should be ruled out in tournaments with many participants.

Accordingly, if one is to solve the above maximization problem, accounting for a positive z, the FOC is given by the following equation, $(1-\epsilon)\, \frac{\partial Ep_{t,j}}{\partial \sigma_{t,j}} E\pi_{t,j} + (1-\epsilon)\, Ep_{t,j} \frac{\partial E\pi_{t,j}}{\partial \sigma_{t,j}} = 0$. Using the implicit function theorem, the following relationship can be found, $\frac{\partial \sigma_{t,j}}{\partial EA_{t,i}} = -\frac{\partial Ep_{t,j}}{\partial EA_{t,i}} / 2\frac{\partial Ep_{t,j}}{\partial \sigma_{t,j}}$. Bearing in mind that, $\frac{\partial Ep_{t,j}}{\partial EA_{t,i}} < 0$, $\frac{\partial \sigma_{t,j}}{\partial EA_{t,i}}$ must always be greater than zero. This relationship implies that the closer any innovator i gets to innovator j the greater the risk that innovator j must use. Thus, noting that $\Delta A_{t,j} = \Delta A^{\zeta}_{t-1,j} n^{\xi}_{t,j} - \frac{c\Delta A_{t-1,j}}{s_{t-1,j}} + \sigma_{t,j} z_{t,j}$ the greater $\sigma_{t,j}$ is, the greater $\Delta A_{t,j}$ will be.

This result, which shows that in N-N tournaments with many participants an increase in tournament competition will lead innovators to take more risk, increasing the magnitude of ΔA, is equivalent to that of Beath Katsoulakos and Ulph (1989), who note that the more one feels a competitors's breath behind his back the more he is forced to run. It also establishes that risk can be an endogenous choice variable, adding to the findings of Dasgupta and Maskin (1986) and Klette and de Meza (1986), who found that patent races yield excessive risky technologies.

4.4 Introducing a growth framework

In this section I will introduce the main aspects of the growth model, which is broadly based on Aghion and Howitt (1992). Unless otherwise stated all the assumptions included in the first part of the chapter continue to apply. Specifically, there are three classes of tradable objects. The first one is labour, the second one is a non-storable consumption good and the third one is an intermediate good. In addition, there is a continuum of infinitely-lived individuals, with identical intertemporal additive preferences, which are defined over lifetime consumption and a constant rate of time preference.

Assuming no disutility from supplying labour, there are three categories of labour. The first one is unskilled workers x. These workers are all equipped with one unit of labour and are used for producing an intermediate input, which will be employed in the production of the consumption good. Similar to Aghion and Howitt (1992), unskilled workers can also function as firms whose aim is to produce the consumption good. The second category is skilled workers in the form of research workers n. Both skilled and unskilled workers are homogeneous, operate in an environment of perfect labour mobility and can exchange roles. In order to avoid confusion, I will assume that research workers will not be used for production if they have already been used in developing the winning innovation.[102] Furthermore, for simplicity, assuming no population growth, the total number of research workers n and production workers x is equal to $L > 1$, i.e.,

$$L = x_t + n_t \tag{4.30}$$

[102] One can assume that there exist unions that forbid such practices.

The third category of labour is innovators, the number of innovators who decide to take part in a tournament is $1 \leq v_t < L$; thus $j \in [1, L)$. Contrary to production workers and research workers innovators are heterogeneous. Innovators are assumed to be risk-neutral individuals and their role is to form the idea that will become an innovation, where each innovation consists of the invention of a new intermediate good, whose use as an input allows more efficient methods to be used in producing the consumption good. Innovators employ research workers and create an innovation using equation (4.28). However, as Jones (1998) notes, for this class of models growth stops being endogenous unless technology exhibits increasing returns to scale. Subsequently, in a fashion similar to Romer (1990), $\zeta + \xi > 1$.

Since no credit market is supposed to exist, all non-research workers consume their wage at each instant and research workers receive no payment unless they win the tournament, in which case they are paid a fixed percentage ϵ of the revenues from the innovation that they have created. The remaining revenues will be transferred to the innovator. If an innovator fails to win a tournament, since the research workers that he used will receive no salary, they have no option but to be employed in production.

Similar to the benchmark model, the consumption good is produced in a perfectly competitive market by a firm that licenses the patent from the innovator, using an intermediate good x_t with productivity ΔA_t, in the following fashion,

$$y_t = \Delta A_t^{\alpha} x_t^{b}, \ \{\alpha, b\} > 0 \tag{4.31}$$

In equation (4.31), y_t represents the output produced using the innovation of the tournament's winner j. Since, no matter who wins the tournament, there is only one type of consumption good, I will abstain from attaching a subscript to y_t.

The time-line of the model is the following. Competitors employ research workers and start their research while participating in a tournament. At the beginning of the tournament innovators make all the irreversible decisions regarding innovation, choosing what type of innovation path to follow and how many research workers to employ. After the tournament they license their innovation to a production firm. Production will take place immediately before the next tournament commences.

4.4.1 Solving the model

In this section I will solve the model. Specifically, the research workers $n_{t,j}$ that innovator j employs receive a payment $w_{t,j}$ that is equal to an ϵ percentage of the expected revenues from the innovation that they expect to create. If they fail to win they will receive no payment. Therefore, the wage that research workers receive can be found from the following relationship,

$$w_{t,j} = Ep_{t,j} \frac{\epsilon E\pi_{t,j}}{n_{t,j}} \tag{4.32}$$

Since the consumption good is produced in a perfectly competitive market, similar to Aghion and Howitt (1992), the profits from the sale of the consumption good $\pi_{t,j}$ are,

$$\pi_{t,j} = b\Delta A_{t,j}^{\alpha} x_{t,j}^{b} - w_{t,j} x_{t,j} \tag{4.33}$$

where $w_{t,j}x_{t,j}$ expresses the wage that the production workers will receive. Substituting equation (4.33) in equation (4.32) one can derive the expected wage $Ew_{t,j}$ as,

$$Ew_{t,j} = \frac{b\Delta A_{t,j}^{\alpha} x_{t,j}^{b}}{\frac{n_{t,j}}{\epsilon Ep_{t,j}} + x_{t,j}} \tag{4.34}$$

The innovator maximizes its expected revenues with respect to the research workers that he intends to use, accounting for equation (4.28). The maximization problem that each innovator solves is,

$$\max_{n_j} \sum_{t=1}^{\infty} \beta^t (1-\epsilon) Ep_{t,j} E\pi_{t,j} \tag{4.35}$$

$$\text{s.t. } E\Delta A_{t,j} = \Delta A_{t-1,j}^{\varsigma} En_{t,j}^{\xi} - \frac{c\Delta A_{t-1,j}}{s_{t-1,j}}$$

$$\Delta A_0 \geq 0$$

where ΔA is used as a state variable. In equation (4.35), the time horizon is between t and ∞ because the innovator may win more than one tournaments. Through the above problem the innovator maximizes his expected profits accounting explicitly for all the re-innovation that will take place at time t. This is because $Ep_{t,j}(A_{t,j}, A_{t,i})$ accounts for the technologies of all the other $i \neq j$ innovators, including the technologies that they develop by re-innovating. Furthermore, he also implicitly accounts for all future innovations that will be based (due to re-innovation) on his technology. This line of thinking suggests that the innovators accounts for both lagging and leading breadth.

In the steady state (where $n_{t+1,i} = n_{t,i} = n$) all innovators are expected to develop innovations of non-changing magnitude ΔA. Thereby, the distance between innovators is not expected to fluctuate. Subsequently, if λ does not change, the ratio $P_t = \frac{Ep_{t,j}}{Ep_{t-1,j}}$ should be equal to one. In total, the expected n is given by the following FOC,

$$En = \left(\left(\frac{P\beta}{\xi} \right)^{1-\varsigma} \left(1 + \frac{c}{s}\right)^{\varsigma} \right)^{\frac{1}{\varsigma+\xi-1}} \tag{4.36}$$

In what follows I will display that the comparative statics of section 3 still apply. In detail, the first way through which λ can affect innovation indicates that an increase in tournament competition (caused by an increase in λ) can be detrimental for innovation. Specifically, as λ increases and innovators get closer (increasing $A_{t,i}$), the expected probability that innovator j has of winning the tournament is reduced, reducing $P_{t,j} = \frac{Ep_{t,j}}{Ep_{t-1,j}}$. However, equation (4.36) suggests that in the steady state, if $\varsigma < 1$, any increase in λ, which decreases P, should lower n, negatively affecting innovation. Furthermore, the second way that a change in λ can affect innovation reverses the above result, examining how the followers will respond. This result is not based on the assumptions of the growth model. Thus, its intuition is identical to the one of section 3.

The third way through which λ affects ΔA, similar to section 3, concentrates on the increase in risk that innovators are forced to adopt when the tournament becomes N-N with many participants. Specifically, innovators maximize expected profits $(1-\epsilon) Ep_{t,j}\pi_{t,j}$ with respect to $\sigma_{t,j}$. Since they are not aware of future realization of z they can only solve a static problem. Following the same reasoning as in section 3, if one is to solve this maximization problem, using equations (4.34)-(4.33), accounting for a positive z, the FOC is given by the following equation, $0 = \frac{\partial Ep_{t,j}}{\partial \sigma_{t,j}} \frac{(1-\epsilon)E\pi_{t,j}n_{t,j}}{n_{t,j}+Ep_{t,j}x_{t,j}}$. Using the implicit function theorem, the following relationship can be found, $\frac{\partial \sigma_{t,j}}{\partial EA_{t,i}} = -\frac{\partial Ep_{t,j}}{\partial EA_{t,i}} / \frac{\partial Ep_{t,j}}{\partial \sigma_{t,j}}$. Bearing in mind that, $\frac{\partial Ep_{t,j}}{\partial EA_{t,i}} < 0$, $\frac{\partial \sigma_{t,j}}{\partial EA_{t,i}}$ must always be greater than zero. The above intuition suggests that in N-N tournaments with many participants an increase in tournament competition will lead innovators to take more risk, increasing the magnitude of ΔA.

4.5 The link between patent breadth and growth

Bearing in mind that the previous sections have indicated a possible non-monotonic relationship between patent breadth and innovation (production), this section examines if this non-monotonic relationship exists in the context of this model. Noting that I lack a data set that would allow me to calibrate the model, or even an exact function for knowledge spillovers and $Ep_{t,j}\left(A_{t,j}, A_{t,i}\right)$, it is best to view this section as a numerical exercise, run for educational purposes. Subsequently, all the values/functions that I will be using during this experiment are *ad hoc*, even though they accord to what the literature has been using in similar cases. Nevertheless, when in doubt (such as with ϵ), I experimented with a whole range of values. Accordingly, in this section I will try and find the optimal patent breadth, the one that maximizes the economy's output growth rate. If such an optimal patent breadth exists, then there must be some form of concavity between output growth rate and patent breath.

With the above in mind, in order to account for the joint effects of λ on the economy's output growth rate I run a numerical experiment over a series of tournaments, gradually increasing the degree of technological competition by increasing the value of λ in each consecutive tournament. It should be noted that in order to avoid any unexpected effects caused by the randomness of z, each tournament consisted of 20 periods during which λ

remained steady. It is the mean rate of output growth from these 20 periods that I used as the output growth rate of each individual tournament.

Specifically, for each of the 20 periods (denoted by t) within a tournament I numerically solved the problem of equation (4.35) and run equations (4.28)-(4.30), (4.33)-(4.34) for 100 heterogenous innovators. Throughout this numerical experiment the technology of innovator i was equal to the ratio of $\frac{A_{t,i}}{A_{t,j}}$, where j is the winner of period t. Furthermore, I allowed the probability function to be equal to, $Ep_{t,j}\left(A_{t,j}, A_{t,i}\right) = 1 - 0.5\exp\left(EA_{t,i} - EA_{t,j}\right)$, which accords well to the assumptions made about $Ep_{t,j}\left(A_{t,j}, A_{t,i}\right)$, where the 0.5 was included just in case the two innovators had identical technologies. As an alternative, I used the probability function derived in Appendix one.

In the first period of each tournament a starting technology, randomly distributed (using a Normal distribution) in the interval $[1, \delta]$, was assigned to each innovator. This technology did not change between tournaments. Therefore, at the first period of each tournament all innovators had the same starting value as in the past one. This intuition implies that some innovators had a starting technology that was close to 1 and some close to δ. In the same fashion, each innovator had a different z, randomly distributed (using a Normal distribution) in the interval $[-\delta, \delta]$, which varied with each period. The starting value of σ was zero, because the starting tournament was not supposed to be a highly competitive tournament. However, with each tournament σ gradually increases until it becomes equal to 1 in the last tournament.

With respect to spillovers, I used the following functional form, $s_{t,j} = \sum_{1}^{v_t - j} \gamma_i \Delta A_{t,i}$, which treats knowledge spillovers as a weighted sum of the innovations created by all innovators except j. In the latter equation, $\gamma_i \geq 0$ indicates the weight with which the technology of each innovator entered the spillover's function, where, similar to Hall Jaffe and Trajtenberg (2000), not all innovations find equal use in generating knowledge spillovers. Subsequently, similar to Panagopoulos (2003), I allowed the innovators who were close to the top of the quality ladder to generate more knowledge spillovers compared to the ones that are further down. Following this type of reasoning, in this numerical experiment γ_i was equal to the inverse of innovator i's ranking. Thus, the 50th innovator had a $\gamma_i = 1/50$.

Bearing in mind that in this model the innovator and the research workers share the profits, I allowed the innovator to have an $\epsilon = 40\%$ share of the profits. Noting that the role of the innovator in this framework was very similar to the one in reality played by a venture capitalist, an $\epsilon = 40\%$ accords with the average percentage of firm stock that venture capitalists get by providing firms with capital and expertise. For b I used the share of labour in US production which is 0.33 and for α the share of capital, which is 0.7.[103] Since, production workers and research workers are homogeneous and employ similar production functions (the production function for the intermediate input uses ΔA and x in a fashion similar to the way equation (4.28) employs ΔA and n) I used $\zeta = 0.7$ and $\xi = 0.33$. Finally, L was 100, while in accordance with the recent NSF data (suggesting that research workers are less that 1% percent of the US working population), the starting values for x and n were 99 and 1 respectively.

On par with Lerner (2004), who examines 150 years of patent protection, this numerical experiment was repeated for 150 tournaments. In these tournaments λ started from

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103 These numbers are taken from Mankiw, Romer, and Weil (1992).

being zero in the first tournament and become one in the 150th tournament. Hence, each tournament become more competitive. The number of participants was derived from equation (4.29), where C was arbitrarily chosen as 70% of the winner's expected revenues from the innovation. Thus, in order for an innovator to find it profitable to participate in the tournament his expected revenues must be equal to at least seventy percent of the winner's. If one is to increase C then it becomes harder to take part in the tournament, while any decrease in C makes it easier. Bearing the above in mind, in the first tournaments, where innovators had starting technologies that were positioned far apart, only a few had an F that fulfilled this requirement, while as the tournament became more competitive, more innovators fulfilled equation (4.29).

Running a numerical experiment for $\delta = 10$, which suggests that the 100 competitors were initially positioned far from each other, the humped shaped relationship of figure 4.3 was derived. *Ad hoc* as the above assumptions may be, this shape does not change drastically if one is to alter ϵ (in the range of $15\% - 60\%$, which is the usual share of profits a venture capitalist gets), δ (for values between 5 and 20, which allow for some observable heterogeneity among innovators), C (for values that do not make it either impossible or too easy to participate, i.e. between 40% and 90%), or if one is to use the alternative probability function. What changes is the turning point and the steepness of the curve.

4.6 Conclusions

Recent findings by Lerner (2004) point to a non-linear relationship between patent strength and innovation. The aim of this chapter was to offer a theoretical explanation for this non-linear relationship. The model is built upon a patent race in which many heterogeneous innovators participate. In this model, innovation is sequential. Hence, current innovation builds on past technology creating current technology. Therefore, the tournament's winner is in a better position to win the future tournament, since he has the more advanced technology. However, depending on the level of patent protection, the other innovators can re-innovate around the winner's patent and create an innovation of similar magnitude. Subsequently, if patent protection is weak the innovators who failed to win the tournament will manage to re-innovate around the winner's patent and position themselves close to the winner's technology. The closer they get the more tournament competition increases, because all innovators start the tournament from similar starting points.

As the model shows, even though higher patent protection increases the innovator's incentives to innovate it leads to less tournament competition. However, highly competitive tournaments, such as neck and neck ones, lead to greater innovations because innovators are forced to use high-risk innovation strategies. Such strategies can potentially lead to great discoveries. Furthermore, compared to non competitive tournaments, in a competitive tournament more innovators will find it profitable to enter the tournament, because innovators have comparable technologies and comparable chances of winning the tournament. The more the innovators who enter the tournament the more the available knowledge spillovers and the greater the resulting innovation.

In a nutshell, an increase in patent protection increases the incentives to innovate, but also leads to less knowledge spillovers and less risky research strategies. Simulating the model, the above are combined in an inverted U relationship between patent protection and growth. For future research, one could run a more detailed simulation calibrated using US-EU data. This would be interesting on account of the considerable increase in US patent protection in the 1980s and the current EU debate on following the US example. As the model suggests, it is important to know on what side of the curve the economy is before increasing (or decreasing) patent protection.

4.A Appendix one

Working in continuous time, without loss of generality equation (4.28) can be expressed as, $dA_j\left(t\right) = s(t)A\left(t\right)_j^{\varsigma} n_j^{\xi} dt + \sigma\left(A\right)_j dz\left(t\right)_j$. As Malliaris and Brock (1987, ch. 2, pg. 101, theorem 7.6) note, the probability density function ϕ of the innovator's technology can be written, using the *Kolmogorov's backward equation* as, $\frac{1}{2}\sigma_j^2\phi_{A_j}^{''} - sA_j^{\varsigma}n_j^{\xi}\phi_{A_j}^{'} - \frac{d\phi}{dt} = 0$. Assuming that the distribution of A does not change, making the density function ϕ time invariant, the above differential equation will give the following solution, $\phi = c\exp\left(\frac{2sEA_j^{\varsigma+1}n_j^{\xi}}{\sigma_j^2}\right)$, where c is a constant. Based on the latter equation, innovator j's expected probability of innovating to a technology level that is between some minimum technology level A_0 and the upper technology limit $\bar{A}$, is given by, $Ep\left(\bar{A} > EA_j > A_0\right) = c\int_{A_0}^{\bar{A}} \exp\left(\frac{2sEA_j^{\varsigma+1}n_j^{\xi}}{\sigma_j^2}\right) dA$ and it should be equal to 1; since $A_j \in (A_0, \bar{A}]$. Thereby one can express innovator j's expected probability of innovating to a technology level A_j that even though it is greater than A_0 it is less than the expected technology level created by innovator i as, $Ep\left(EA_i > EA_j > A_0\right) = c\int_{A_0}^{EA_i} \exp\left(\frac{2sEA_j^{\varsigma+1}n_j^{\xi}}{\sigma_j^2}\right) dA$. Moreover, since $Ep\left(\bar{A} > EA_j > A_0\right) = Ep\left(\bar{A} > EA_j > EA_i\right) + Ep\left(EA_i > EA_j > A_0\right)$, the expected probability that innovator j has of over passing innovator i is given by,

$$\begin{aligned} Ep_j &= Ep\left(\bar{A} > EA_j > A_0\right) - Ep\left(EA_i > EA_j > A_0\right) \\ &= 1 - c\int_{A_0}^{EA_i} \exp\left(\frac{2sEA_j^{\zeta+1}n_j^{\xi}}{\sigma_j^2}\right) dA \\ &= 1 - \frac{cn_j^{-\xi}\sigma_j^2}{2sEA_j^{\zeta}}\left[\exp\left(\frac{2sEA_i^{\zeta+1}n_j^{\xi}}{\sigma_j^2}\right) - \exp\left(\frac{2sA_0^{\zeta+1}n_j^{\xi}}{\sigma_j^2}\right)\right] \end{aligned}$$

It should be noted, that the main drawback of this approach, even though it leads to similar results as the rest of the chapter, is its increased mathematical difficulty (stemming from the use of continuous time), and its reliance on graphical interpretations.

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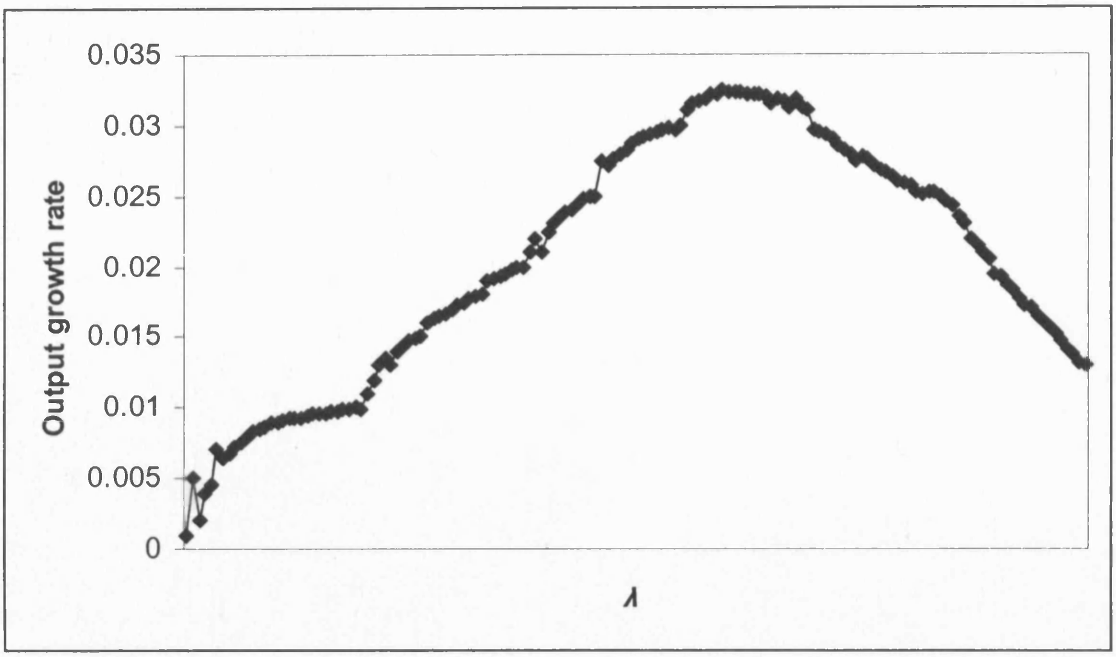

Fig. 5.3. The x axis represents λ over 150 tournaments. In the first tournament λ is zero, while in the last one λ is one.