When Does Patent Protection Stimulate Innovation?

Andreas Panagopoulos

Discussion Paper No. 04/565

November 2004

Department of Economics
University of Bristol
8 Woodland Road
Bristol BS8 1TN

When Does Patent Protection Stimulate Innovation?

Andreas Panagopoulos*

University of Bristol

November 17, 2004

Abstract

Patents act as an incentive to innovate. However, as this paper argues, patents can lead the patent holder to rest on his laurels and at the same time discourage some innovators from innovating, reducing knowledge spillovers. The combined result of the above suggests an inverse U relationship between patent protection and output growth.

Keywords: Intellectual property, patent races, growth.

JEL No: K0, O11, 034

*Contact email, uctpapa@ucl.ac.uk

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'Donaghue, 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 paper 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 paper will also concentrate on two additional ways through which greater patent protection can affect innovation. The first one 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 (because all innovators will be able to freely copy the latest innovation) forcing competitors to adopt risky innovation strategies. Such strategies can potentially lead to breakthroughs as well as failures. To offer an example of how strong patent protection can effectively lead an innovator to rest on his laurels, 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.

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 the paper 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 the paper, 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 paper'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. This definition 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 Scotchmer and Green (1995) focus on the division of profits. 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 is the courts' attitude towards infringement. 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.

This paper is not the only one examining patent breadth in the context of a tournament.[1] Tournaments have also been studied by Denicolò (2000 and 1996), however, the emphasis here is on the patent breadth that maximizes output growth. Therefore, the model distances itself from Denicolò (2000), Chang (1995), Gilbert and Shapiro (1990), Klemperer (1990) and Nordhaus (1969) who concentrate on social welfare.

In addition, this is not the only paper that finds a non-linear relationship between patent protection and innovation/output.[2] Horowitz and Lai (1996), show that there is a non-monotonic 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.

The model is not without its drawbacks. For example, in order to clarify the analysis, I have

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

[2] See Gallini (2002) for a survey.

labored 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 the paper is the following. Section 2 introduces the tournament and the way technology is generated. Section 3 displays the model's main properties. Section 4 extents the model by introducing a simple growth framework, while section 5 contains the simulation and it is followed by the conclusions.

2 Assumptions

In what follows the paper 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 paper, 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.[3] 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 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 the paper I will not offer any microeconomics structure backing these two assumptions. This will be included in the second part of the paper.

[3] 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.

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 paper's results and final formulas.

Innovators innovate sequentially.[4] 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,[5] (i.e. $A_t = \sum_0 \Delta A_t$), 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 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

[4] 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).

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

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.[6] 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,

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

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.[7]

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.

[6] 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, $\lambda > 0$.

[7] In reality, even though (in the US) patent breadth is decided by the PTO, the courts and Congress, it is up to the firm to seek litigation if it finds out that rivals have used its technology.

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 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,

$$\begin{aligned} \Delta A_{t,j} &= \Delta A_{t-1,j}^{\zeta} n_{t,j}^{\xi} - \frac{c\Delta A_{t-1,j}}{s_{t-1,j}} + \sigma_{t,j} z_{t,j} \\ c &> 0,\ \sigma_{t,j} \in [0,1] \end{aligned} \tag{2}$$

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 (2) 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 (2), $\Delta A_{t-1,j}^{\zeta} n_{t,j}^{\xi}$ 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.[8] Since $\sigma_{t,j}z_{t,j}$ can attain negative values it is possible for $\Delta A_{t,j}$ to be less than zero.[9] 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 $\Delta A_{t,j}$.[10] 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 far costly and outdated (when compared to the USA TV technology of its time).[11]

In equation (2), $\Delta A_{t,j}$ 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, bearing in mind 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 (2), 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

[8]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).

[9]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 (2) is always greater than zero.

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

[11]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).

equation (2)) 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 innovator j with an expected probability $Ep_{t,j}$ of winning the tournament. I will allow $Ep_{t,j}\left(A_{t,j},\, A_{t,i}\right) \in [0,1]$, $i \neq j$, $i \in [1,\, v_t - j]$ 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.[12]

Intuitive as $Ep_{t,j}\left(A_{t,j},\, A_{t,i}\right)$ 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 (2) 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 paper, is its increased mathematical difficulty, and its reliance on graphical interpretations.

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 value of entering the current tournament. In doing so, I will treat the decision to innovate as an investment decision.

[12] 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.

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.[13] 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,

$$F_{t,j} = (1 - \epsilon)\, Ep_{t,j}\pi_{t,j} - C \tag{3}$$

In equation (3), $F_{t,j}$ 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 $\Delta A_{t,j}$.

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 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

[13] See also, Grenadier (1996), Kulatilaka and Perotti (1998), Lambrecht and Perraudin (1997).

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 $Ep_{t,j}(A_{t,j},\, A_{t,i})$ 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 rational 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 $Ep_{t,j}(A_{t,j},\, A_{t,i})$. 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 (3), 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 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 paper continue to apply. Specifically, there are three classes of tradable objects. The first one is labor, 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 labor, there are three categories of labor. The first one is unskilled workers x. These workers are all equipped with one unit of labor 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 labor mobility and can exchange roles. For simplicity, assuming no population growth, the total number of research workers n and production workers x is equal to $L > 1$, i.e.,

$$L = x_t + n_t \tag{4}$$

The third category of labor 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 (2). 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,

$$y_t = \Delta A_t^{\alpha} x_t^{b},\ \{\alpha, b\} > 0 \tag{5}$$

In equation (5), 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.

4.1 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,

$$w_{t,j} = Ep_{t,j}\frac{\epsilon E\pi_{t,j}}{n_{t,j}} \tag{6}$$

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,

$$\pi_{t,j} = b\Delta A_{t,j}^{\alpha} x_{t,j}^{b} - w_{t,j} x_{t,j} \tag{7}$$

where $w_{t,j}x_{t,j}$ expresses the wage that the production workers will receive. Substituting equation (7) in equation (6) one can derive the expected wage $Ew_{t,j}$ as,

$$Ew_{t,j} = \frac{b\Delta A_{t,j}^{\alpha} x_{t,j}^{b}}{\frac{n_{t,j}}{\epsilon Ep_{t,j}} + x_{t,j}} \tag{8}$$

The innovator maximizes its expected revenues with respect to the research workers that he intends to use, accounting for equation (2). The maximization problem that each innovator solves is,

$$\max_{n_j} \sum_{t=1} \beta^t (1-\epsilon) Ep_{t,j} E\pi_{t,j} \tag{9}$$

$$\begin{aligned} \text{s.t. } E\Delta A_{t,j} &= \Delta A_{t-1,j}^{\zeta} En_{t,j}^{\xi} - \frac{c\Delta A_{t-1,j}}{s_{t-1,j}} \\ \Delta A_0 &\geq 0 \end{aligned}$$

where ΔA is used as a state variable. In equation (9), 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,

$$En = \left(\left(\frac{P\beta}{\xi} \right)^{1-\zeta} \left(1 + \frac{c}{s} \right)^{\zeta} \right)^{\frac{1}{\zeta+\xi-1}} \tag{10}$$

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 (10) suggests that in the steady state, if $\zeta < 1$, 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 (8)-(7), 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.

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 $Ep_{t,j}(A_{t,j}, A_{t,i})$, 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 (9) and run equations (2)-(4), (7)-(8) 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, $s_{t,j} = \sum_{1}^{v \neq j} \gamma_i \Delta A_{t,i}$, 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 labor in US production which is 0.33 and for α the share of capital, which is 0.7.[14] 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 (2) 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 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 (3), 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

[14] These numbers are taken from Mankiw, Romer, and Weil (1992).

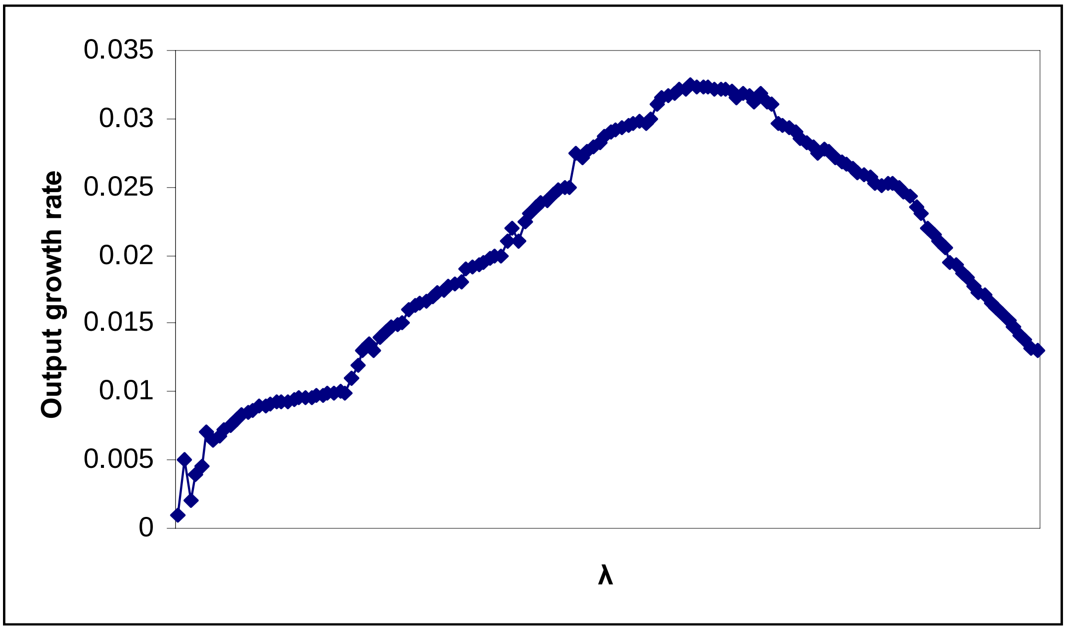

Figure 1: The x axis represents λ over 150 tournaments. In the first tournament λ is zero, while in the last one λ is one.

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 (3).

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 1 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.

6 Conclusions

Recent findings by Lerner (2004) point to a non-linear relationship between patent strength and innovation. The aim of this paper is 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.

Appendix one

Working in continuous time, without loss of generality equation (2) can be expressed as, $dA_j\,(t) = s(t)A\,(t)_j^{\zeta}\,n_j^{\xi}dt + \sigma\,(A)_j\,dz\,(t)_j$. 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, $\frac{1}{2}\sigma_j^2\phi''_{A_j} - sA_j^{\zeta}n_j^{\xi}\phi'_{A_j} - \frac{d\phi}{dt} = 0$. 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, $\phi = c\exp\left(\frac{2sEA_j^{\zeta+1}n_j^{\xi}}{\sigma_j^2}\right)$, 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, $Ep\left(\bar{A} > EA_j > A_0\right) = c\int_{A_0}^{\bar{A}}\exp\left(\frac{2sEA_j^{\zeta+1}n_j^{\xi}}{\sigma_j^2}\right)dA$, 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, $Ep\,(EA_i > EA_j > A_0) = c\int_{A_0}^{EA_i}\exp\left(\frac{2sEA_j^{\zeta+1}n_j^{\xi}}{\sigma_j^2}\right)dA$. Moreover, since $Ep\left(\bar{A} > EA_j > A_0\right) = Ep\left(\bar{A} > EA_j > EA_i\right) + Ep\,(EA_i > EA_j > A_0)$, the expected probability that innovator j has of over passing innovator i is given by,

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

References

[1] Aghion, P., and Howitt, P., (1992), 'A Model of Growth Through Creative Destruction', Econometrica, 60, pp. 323-351.

[2] Baldwin, W., and Scott, J., (1987), 'Market Structure and Technological Change' in Fundamentals of Pure and Applied Economics, Vol. 17, Harwood Academic Publishers, New York.

[3] Beath, J., Katsoulakos, Y. and Ulph, D., (1989), 'Strategic R&D Policy', Economic Journal, Vol. 99, No. 395, pp. 74-83.

[4] Braithwaite, J., and Drahos P., (2000), 'Global Business Regulation', Cambridge University Press.

[5] Cohen, W., Nelson, R., and Walsh, J., (2000), 'Protecting Their Intellectual Assets: Appropriability Conditions and Why US Manufacturing Firms Patent or Not?', NBER Working Paper 7552.

[6] Dasgupta, P., and Maskin, E., (1986), 'The Simple Economics of Research Portfolios', Economic Theory Discussion Paper 105, Cambridge University.

[7] Dasgupta, P., and Stiglitz, J., (1980), 'Entry, Innovation, Exit: Towards a Dynamic Theory of Oligopolistic Industrial Structure', European Economic Review, 15, pp. 139-158.

[8] Dixit, K., and Pindyck, R., (1994), 'Investment Under Uncertainty', Princeton University Press, Princeton New Jersey.

[9] Gallini, N., (2002), 'The Economics of Patents: Lessons from Recent US Patent Reform', Journal of Economic Perspectives, Vol. 16, No. 2, Spring, pp. 131-154.

[10] Grenadier, S., (1996), 'The Strategic Exercise of Options: Development Cascades and Overbuilding in Real Estate Markets', Journal of Finance, 51, Dec., pp. 1653-1679.

[11] Hall, B., Jaffe, A., and Trajtenberg, M., (2000), 'Market Value and Patent Citation: A First Look', NBER Working Paper, No. 7741.

[12] Hall, B., and R., Ziedonis, (2001), 'The Patent Paradox Revisited: An Empirical Study of Patenting in the US Semiconductor Industry, 1979-1995', The RAND Journal of Economics, No. 32:1, pp. 101-128.

[13] Harris, C., Vickers, J., (1987), 'Racing with Uncertainty', Review of Economic Studies, 54, pp. 1-21.

[14] Jones C., (1998), 'Growth With or Without Scale Effects?', Working Paper, Stanford University.

[15] Jones, C., (2001), 'Was the Industrial Revolution Inevitable? Economic Growth Over the Very Long Run', Advances in Macroeconomics, 2001, 1 (2), Article 1.

[16] Klette, T., and de Meza, D., (1986), 'Is the Market Biased Against R&D?', The RAND Journal of Economics, 17, pp. 133-139.

[17] Kulatilaka, N., and Perotti, E., (1999), 'Strategic Growth Options', Management Science, 44, Aug., pp. 1021-1031.

[18] Lambrecht, B., and Perraudin W., (1997), 'Real Options and Pre-emption', University of Cambridge, JIMS Working Paper, No. 15/97.

[19] Lerner, J., (1995), 'The Importance of Trade Secrecy: Evidence from Civil Litigation', Working Paper, Harvard University.

[20] Lerner, J., (2004), '150 Years of Patent Protection', American Economic Review Papers and Proceedings, 92 pp. 221-225.

[21] Loury, G., (1979), 'Market Structure and Innovation', Quarterly Journal of Economics, XCIII, Aug., pp. 395-410.

[22] Malliaris, A., Brock, W., (1987), 'Stochastic Methods in Economics and Finance', Bliss C. and Intriligator, M., eds., Advanced Textbooks in Economics, Vol. 17, North Holland.

[23] Mankiw, G., Romer, D., Weil, D., (1992), 'A Contribution to the Empirics of Economic Growth', The Quarterly Journal of Economics, Vol. 107, No. 2, May, pp. 407-37.

[24] Matutes, C., Regibeau, P., and Rockett, K., (1996), 'Optimal Patent Protection and the Diffusion of Innovation', The RAND Journal of Economics, Vol. 27, pp. 60-83.

[25] Nordhaus, W., (1969), 'Invention Growth and Welfare: A Theoretical Treatment of Technological Change', MIT Press, Cambridge.

[26] O'Donaghue, T., Scotchmer, S., and Thisse, J., (1998), 'Patent Breadth, Patent Length and the Pace of Technological Progress', Journal of Economics and Management Strategy, 7, pp. 1-32.

[27] Panagopoulos, A., (2003), 'Understanding When Universities and Firms Form RJVs: The Importance of Intellectual Property Protection', International Journal of Industrial Organization, Vol. 21 (9), pp. 1411-1433.

[28] Reinganum, J., (1989), 'The Timing of Innovation: Research Development and Diffusion', in R. Schmalensee and R. Willig, (eds.), Handbook of Industrial Organization Vol. 1, New York:, North-Holland.

[29] Reinganum, J., (1984), 'Practical Implications of Game Theoretical Models of R&D', American Economic Review, Papers and Proceedings, 74, pp. 61-66.

[30] Romer, P., (1990), 'Endogenous Technological Change', Journal of Political Economy, 98, No. 5, Oct, pp. S71-S202.

[31] Rosenberg, N., (1996), 'Uncertainty and Technological Change. The Mosaic of Economic Growth?', in Ralph Landau and Gavin Wright, Stanford, Stanford University Press, pp. 334-356.

[32] Segerstrom , P., (1998), 'Endogenous Growth Without Scale Effects', Michigan State University, Working Paper.