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Patent Protection of Basic Research in Cumulative Innovation

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Abstract

There is an ongoing debate on what is the optimal patent protection of basic technologies in cumulative innovations. I study the optimal patent protection of basic research in a two-stage patent race model with basic research at the ...rst stage and commercial product development at the second stage. I ...nd the following. Investment in basic research initially increases and then decreases in the degree of patent protection of the basic research, while investment in commercial development always decreases in the degree of protection of the basic research. The welfare-maximizing degree of protection of basic research decreases in the monopoly rent from the basic innovation, increases in the marginal cost of the basic innovation, increases in the consumer surplus from the basic innovation and decreases in the consumer surplus from the commercial product. Basic research ...rms overinvest (underinvest) relative to the social planner at intermediate degrees (low and high degrees) of protection of basic research. Commercial development ...rms overinvest (underinvest) relative to the social planner when the protection of basic research is weak (strong).

JEL Classi...cation: D23, D45, L14

Keywords: cumulative innovation, basic research, patent protection, two-stage patent races.

1 Introduction

Cumulative innovation is a common phenomenon. In high technology industries such as biotechnology, pharmaceuticals, computers and electronics, products are the result of cumulative innovation. In cumulative innovation, an initial discovery is used for a subsequent discovery. For example, the basic research for the diagnostic test for the BRCA1 breast cancer gene, the basic research for the synthetic Hepatitis B vaccine and the basic research for multiple drugs for cancer treatment were conducted in universities and research ..rms, while the diagnostic test, the vaccine and the drugs, respectively, were developed by commercial ..rms.

In this paper I focus on cumulative innovation, when the initial discovery is a basic research innovation and the subsequent discovery is commercial product development, and the two discoveries are performed by separate ..rms. It is common that research ..rms and universities specialize in the discovery of basic technologies and license them to commercial ..rms for the development of commercial products. For example, eight out of the top ten biotechnology products in 2002 were developed using licensed university technologies (Edwards et al. 2003). Another example, which emphasizes the scale of licensing of basic technologies is that in 2003 a total of 3,926 U.S. patents were issued to U.S. academic institutions participating in a survey conducted by the Association of University Technology Transfer Managers (AUTM)[1] and these same institutions executed 4,464 licenses and options, and received $1.34 billion U.S. dollars in gross license income (AUTM 2004). The annual economic impact of the licenses of the above institutions on the U.S. economy is estimated to over $21 billion U.S. dollars[2] and the creation of 180,000 jobs (AUTM 1995). Note that these ..gures include only licensings of academic institutions and do not include licensings of research ..rms and their respective contribution to economy, which would increase the impact signi..cantly.

The patent system plays an important role in the process of innovation. It encourages innovation by ensuring that innovators can be remunerated for their R&D investment. Patents protect innovators from imitators, known as backward protec-

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[1]The Association of University Technology Transfer Managers (AUTM) collects and reports survey data on technology licensing at U.S. universities, hospitals and research institutes. The 2003 AUTM Licensing Survey has data on 132 U.S. universities and 26 U.S. hospitals and research institutes.

[2]This estimate includes $4 billion U.S. dollars of pre-production investment (made prior to the sales of licensed products) and $17 billion U.S. dollars of sales of licensed products (AUTM 1995).

tion, and reward innovators for providing the basis for subsequent innovations, known as forward protection. Forward patent protection is provided by both the Patent Office and the courts through the patentability requirement and the patent breadth, which means that if a subsequent innovation is not sufficiently novel or if it falls within the claims of a previous patent, it is found to infringe on that patent. In cumulative innovation, especially when it does not take place within a single firm, the patent system has to ensure that all inventors have sufficient incentives to carry out their part of the research. The challenge is that the commercial value of the entire cumulative innovation is embodied in the application, while the basic innovation has no stand-alone value. The only way the innovator of the basic technology can be compensated for his contribution to the cumulative innovation is through the division of the profits from the commercial application. Strong patent protection of the basic innovation gives the basic innovator more bargaining power as to the division of these profits in the licensing agreement, and leaves the developer of the commercial application with less profit. Therefore, strong patent protection of the basic innovation has two opposing effects on the investment incentives in cumulative innovation. It stimulates the R&D investment in basic research, but discourages the R&D investment in the development of commercial products. The question arises: What is the optimal degree of patent protection of the basic innovation?

The importance of the above question has been recognized by the U.S. and foreign governments, which amend and fine-tune the degree of patent protection of basic research in their respective countries (see Mowery et al. 2004 for a detailed review). Since the 1980s the United States has supported a policy of strong patent protection of basic research. Two influential events marked the beginning of that policy. First, the Bayh-Dole Act of 1980 gave universities the right to patent and exclusively license the results of federally funded research, and encouraged universities to participate in technology transfer activities with commercial companies in order to promote the utilization of inventions arising from federal funding. Second, in 1980 in Diamond vs. Chakrabarty the US Supreme Court ruled that living, manmade microorganisms are patentable and this decision stimulated the patenting of fundamental biotechnology discoveries. Subsequently, in 1984 an amendment to Bayh-Dole removed the time limits on the length of exclusive licenses universities could offer to large businesses, making patented university research more attractive to businesses and strengthening its protection. The patent protection of basic research was further enhanced during the 1980s through a general change in the U.S. policy toward stronger intellectual

property rights.[3] Recently, there has been a common trend across other OECD countries to allow universities and small businesses which perform government research to obtain patents and license their inventions (OECD 2002).[4]

of the ...rst-stage innovation are considered. Third, the paper shows that there is no de...nite answer to the question whether the patent protection of basic research should be weak or strong, but the degree of protection depends on the parameters of the innovation races at the two stages.

The main ...ndings in the paper are as follows. Investment in basic research initially increases and then decreases in the degree of patent protection of the basic research, while investment in product development always decreases in the degree of protection of the basic research. The welfare-maximizing degree of protection of basic research decreases in the monopoly rent from the basic innovation, increases in the marginal cost of the basic innovation, increases in the consumer surplus from the basic innovation and decreases in the consumer surplus from the commercial product. Basic research ...rms overinvest (underinvest) relative to the social planner at intermediate degrees (low and high degrees) of protection of basic research. Commercial development ...rms overinvest (underinvest) relative to the social planner when the protection of basic research is weak (strong).

The paper is organized as follows. Section 2 discusses the relevant patent policy tools for protection of basic research innovations. Section 3 reviews related literature. Section 4 presents the model and its solution, and examines the relationship between patent protection of basic research and investment at the two stages. Section 5 analyzes the welfare-maximizing degree of patent protection of basic research and describes the deviations of the equilibrium investments from the social optimum. Section 6 concludes.

2   Patent Policy Tools

In the U.S. the patent policy is determined by the Patent O¢ ce and by the courts. An inventor ...les a patent application with the Patent O¢ ce, in which he includes a description of the innovation and a set of claims as to what uses of the invention should be protected by the patent. The Patent O¢ ce reviews the application and decides whether the innovation is patentable and what claims to allow. The innovation is patentable if it meets the statutory requirements for patentability: novelty, utility

decide whether or not there is an infringement. If a product is found to infringe a previous patent, the maker of the product needs to license the initial patent in order to be able to continue to market the product legally.

The patent policy has the following tools in determining the degree of patent protection for an innovation: the length of the patent life, the statutory requirement for patentability and the patent claims. While the duration of the patent has been established, the Patent O¢ce and the courts always make decisions using the last two policy tools. In addition, according to Merges and Nelson (1990), while following the law the Patent O¢ce and the courts have signi…cant room for discretion in making decisions. The Patent O¢ce can exercise discretion when deciding what is patentable and what claims to allow on a patent. The courts have discretion in determining whether a patent or a product infringes on a previous patent, and whether a previously issued patent is valid or not.

I use the terminology developed by O'Donoghue (1998) and I follow his paper in placing these two policy tools within the vocabulary used in the R&D literature. The …rst tool, "the patentability requirement", includes the statutory requirements for novelty, non-obviousness and utility. The patentability requirement can be interpreted as a minimum innovation size needed to obtain a patent. In the R&D literature the patentability requirement is also referred to as "novelty requirement", "non-obviousness requirement" or "patentability". The second tool, "the patent breadth", coincides with the claims in a patent. In other words, the patent breadth is the set of products covered by the patent which would be found to infringe it. Alternative terminology for the patent breadth in the R&D literature is "patent scope" and simply "patent protection". The patent breadth can be one of two types "leading patent breadth" and "lagging patent breadth". The lagging breadth is the set of inferior products that infringe on the patent. The leading breadth is the set of superior products, which require further innovation, that infringe on the patent. In the R&D literature the combination of patentability requirement and lagging breadth is also called "backward patent protection" and the combination of patentability requirement and leading breadth is also called "forward patent protection".

In this paper I am concerned with the degree of patent protection of basic research in cumulative innovation. The relevant policy tools for determining that degree, are the patentability requirement and the leading patent breadth. I do not focus on any one of these two tools speci…cally. Instead I view the degree of patent protection of basic research as the result of the joint application of these tools. In the following

model, the government decides the degree of patent protection of basic research,

ex ante licensing makes sure that the second-stage innovator's profit share gives him sufficient incentives to invest. Matutes, Regibeau and Rockett (1996) are concerned about a delay in the diffusion of basic innovations in the absence of patent protection of the basic innovation. In particular, they are concerned that if the basic innovation is not protected, in fear of imitation of the basic technology, the basic innovator is tempted to wait and develop multiple applications of the basic technology before commercializing any of these applications. They recommend that basic innovations receive a patent "scope" protection, which they define as the reserved rights of the basic innovator to develop a certain set of applications of the basic technology, while applications outside of that set can be developed by rivals. In an infinite sequence of innovations, O'Donoghue, Scotchmer and Thisse (1998) propose that patents should provide protection from future innovators and stimulate R&D investment through the leading patent breadth, while O'Donoghue (1998) proposes that this should be done through the patentability requirement, which achieves the same goal without the undesired effect of consolidating market power.

The arguments for weak protection of the first-stage innovation are as follows. Heller and Eisenberg (1998) warn of a tragedy of the "anticommons" in the case of the "privatization" of biomedical research through the patentability of basic biomedical discoveries. They are concerned that the patentability of basic research is stifling downstream innovations in the course of research and product development. Merges and Nelson (1990) raise a concern that in science-based industries, such as the biotechnology industry, broad patents on basic discoveries have an undesired effect on market structure (consolidating market power in a few firms) and the rate of innovation. Nelson (2005) argues that for the same reasons there should be open access to scientific research results, that is basic innovations should receive no patent protection.

This paper is closest in spirit to the papers of Chang (1995) and Denicolo (2000), which attempt to quantify the optimal degree of patent protection of basic research. Chang (1995) shows that the optimal patent scope of the first-stage discovery is a non-monotonic function of its value. In particular, he proposes that broadest protection should be provided to basic inventions in two distinct situations: when a basic

while in the second case the initial innovation itself is very valuable. The policy implication for basic research innovations with no stand-alone value is that they should receive strong patent protection. This paper differs from Chang's in two ways. First, I introduce a patent race at each innovation stage. In Chang's model a single firm

innovation are product development and the second product is an improvement of the ...rst. Denicolo analyzes the patent protection of the ...rst-stage innovation in three distinct regimes, which arise depending on whether the second-stage innovation

innovation determines the bargaining power of the basic innovator in the licensing negotiations, in which the division of the second-stage pro...t is arranged. I assume that the licensing fees paid by the second innovator are equal to a share   of the monopoly rent from the second-stage innovation.

Commercial Development Innovation Race:
Each active symmetric commercial firm i chooses investment x_{i2} in order to

Figure 1: Timing of interactions.

The timing of the interactions in the game is presented in Figure 1. At the beginning of the game the government chooses a degree of patent protection of basic research   in order to maximize expected social welfare. Then each active symmetric basic research ...rm chooses its investment e¤ort x_{i1} and competes in the research innovation race. The ...rst research ...rm to innovate receives a patent and the basic research race ends. The consumers receive the consumer surplus from the basic innovation, s_1. Next, each active symmetric commercial development ...rm chooses its

investment e¤ort x_{i2} and competes in the product development race. The product development race ends with the …rst success and the successful commercial innovator obtains a patent. Because the second patent infringes on the …rst, the second innovator (product developer) has to license the basic technology from the …rst innovator (basic researcher) in order to be able to commercialize the newly developed product. The commercial innovator pays a licensing fee equal to a share of the monopoly rent from the commercial product and markets the product. The consumers receive the consumer surplus from the commercial product, s_2. The solution of this game is a sub-game perfect Nash equilibrium and is found by backward induction.

4.1   Product Development Innovation Race

At the beginning of the product development innovation race, the problem of a symmetric commercial …rm i is to choose its investment e¤ort for that race x_{i2} in order to maximize its expected discounted pro…t:

$$
\begin{aligned}
{}_{i2} &= \int_0^\infty e^{-rt} e^{-\left(\Sigma_{j=1}^{n_2} x_{j2}\right)t} x_{i2}\,(1-\ ) v_2 dt - c_2 x_{i2} \\
&= \frac{x_{i2}}{\sum_{j=1}^{n_2} x_{j2} + r}\,(1-\ ) v_2 - c_2 x_{i2}: \qquad (1)
\end{aligned}
$$

The term $e^{-\left(\Sigma_{j=1}^{n_2} x_{j2}\right)t} x_{i2}$ is the probability density that …rm i is the …rst …rm to innovate in the product development race at time t, in which event at time t it starts receiving a share $(1-\ )$ of the constant ‡ow of monopoly rent from the product innovation, which at time t has present discounted value v_2. At the beginning of the product development race, …rm i commits cost $c_2 x_{i2}$. The term $\frac{x_{i2}}{\Sigma_{j=1}^{n_2} x_{j2}+r}$, which emerges after integration, is the time discounted probability that …rm i is the successful innovator in the development race.

The …rst order condition for expected pro…t maximization is:

$$
\frac{d\ {}_{i2}}{dx_{i2}} = \frac{(X_2 - x_{i2} + r)\,(1-\ )\,v_2}{(X_2 + r)^2} - c_2 = 0; \qquad (2)
$$

where $X_2 = {}_{j=1}^{n_2} x_{j2}$ is the aggregate investment at the second stage. If the …rst order condition is satis…ed …rm i invests e¤ort x_{i2} and participates in the product development race. Otherwise, it stays out of the race.

The second order condition is negative:

$$\frac{d^2 \quad _{i2}}{dx_{i2}^2} = -2\,(X_2 + r)\,(X_2 - x_{i2} + r)\,(1$$

4.2 Basic Research Innovation Race

At the beginning of the basic research innovation race, the problem of a symmetric basic research ..rm i is to choose its investment e¤ort x_{i2} in that race in order to maximize its expected discounted pro..t:

$$
\pi_{i1} = \int_0^\infty e^{-rt} e^{-(\Sigma_{j=1}^{n_1} x_{j1})t} x_{i1} \left(v_1 + \int_0^\infty e^{-r}\, e^{-(\Sigma_{j=1}^{n_2} x_{j2})} \left(\sum_{j=1}^{n_2} x_{j2} \right) v_2 d \right) dt - c_1 x_{i1}
$$

$$
= \frac{x_{i1}}{\sum_{j=1}^{n_1}} \quad \text{[text corrupted/illegible]}
$$

$$X_1 = \frac{v_1 + \frac{X_2}{X_2+r}\, v_2}{c_1} - r$$

$$= \frac{v_1 + \frac{1}{(1-\ )}((1-\ )\, v_2 - rc_2)}{c_1} - r: \tag{8}$$

The degrees of patent protection of basic research, which guarantee that the aggregate investment in basic research X_1 is positive, are $\underline{\ }_{X_1} <\ < \overline{\ }_{X_1}$, where $\underline{\ }_{X_1}$ and $\overline{\ }_{X_1}$ are de..ned in Appendix A.1. If the degree of patent protection of basic research is less than $\underline{\ }_{X_1}$, then the monopoly rent which the basic research innovator will collect from the commercial developer, v_2, will be too small to warrant investment by research ..rms and the basic research race will not take place. If the degree of patent protection of basic research is greater than $\overline{\ }_{X_1}$, then the commercial innovator's rent, $(1-\ )v_2$, will be small and so will be the aggregate investment in product development X_2 and the probability of success in the development race $\frac{X_2}{X_2+r}$. Then the basic research innovator's expected rent from the commercial product, $\frac{X_2}{X_2+r}\, v_2$, will be too small to justify investment in the basic research race.

It follows from (4) and from (8) that the feasible degrees of patent protection of basic research, which guarantee that the aggregate investment in both innovation races is positive, are $\ < \overline{\ }_{X_2}$ and $\underline{\ }_{X_1} <\ < \overline{\ }_{X_1}$. Appendix A.2 derives the degrees of protection which satisfy both of these inequalities and the result is shown in Assumption 2. In the analysis of the equilibrium investment and the social welfare which follows in this paper, I will focus on the degrees of patent protection, which support positive investment in both innovation races and therefore support a true cumulative innovation. Thus Assumption 2 is needed.

Assumption 2 (Feasible degrees of patent protection of basic research) I assume that patent protection of basic research satis..es the following conditions:

$$0 \le\ < \overline{\ }_{X_2} \text{ when } v_1 > rc_1 \text{ and}$$
$$\underline{\ }_{X_1} <\ < \overline{\ }_{X_1} \text{ when } v_1 \le rc_1;$$

which guarantee that the aggregate investment in both innovation races is positive.

Assumption 2 implies that for a typical basic innovation with no stand-alone value ($v_1 = 0$), the interval of feasible degrees of protection of basic research is $\underline{\ }_{X_1} <\ < \overline{\ }_{X_1}$. In that case the basic research is ..nanced entirely through the second-stage product rent and the protection of basic research has to insure that

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Proposition 2 Let $\widehat{x_1} = 1 - \sqrt{\frac{rc_2}{v_2}}$

$$W = \sum_{i=1}^{n_1} \pi_{i1} + \int_0^\infty e^{-rt}e^{-\left(\Sigma_{i=1}^{n_1}x_{i1}\right)t}\left(\sum_{i=1}^{n_1}x_{i1}\right)s_1 dt$$

$$+ \int_0^\infty e^{-rt}e^{-\left(\Sigma_{i=1}^{n_1}x_{i1}\right)t}\left(\sum_{i=1}^{n_1}x_{i1}\right)\left(\sum_{j=1}^{n_2}\pi_{j2} + \int_0^\infty e^{-r}\,e^{-\left(\Sigma_{j=1}^{n_2}x_{j2}\right)}\left(\sum_{j=1}^{n_2}x_{j2}\right)s_2 d\right)dt$$

$$= \sum_{i=1}^{n_1}\pi_{i1} + \frac{X_1}{X_1+r}s_1 + \frac{X_1}{X_1+r}\left(\sum_{j=1}^{n_2}\pi_{j2} + \frac{X_2}{X_2+r}s_2\right): \qquad (9)$$

As was discussed earlier, the term $e^{-rt}e^{-\left(\Sigma_{i=1}^{n_1}x_{i1}\right)t}\left(\sum_{i=1}^{n_1}x_{i1}\right)$, which after integration becomes $\frac{X_1}{X_1+r}$, is the time discounted probability of success in the basic research innovation race and the term $e^{-r}\,e^{-\left(\Sigma_{j=1}^{n_2}x_{j2}\right)}\left(\sum_{j=1}^{n_2}x_{j2}\right)$, which after integration becomes $\frac{X_2}{X_2+r}$, is the time discounted probability of success in the product development innovation race.

5.1 Social Planner

The social planner maximizes the expected social welfare function with respect to aggregate investment at the two innovation stages. Patent protection of basic research is irrelevant in his maximization problem because the social planner makes sure that optimal investments are being made in both innovations. In the social planner's problem ...rms' pro...ts are not necessarily equal to zero and therefore using the de...nitions for π_{i1} and π_{j2} from (5) and (1), respectively, the social welfare function in (9) can be rewritten as:

$$W = \frac{X_1}{X_1+r}(v_1+s_1) - c_1 X_1 + \frac{X_1}{X_1+r}\left(\frac{X_2}{X_2+r}(v_2+s_2) - c_2 X_2\right) \qquad (10)$$

The ...rst-order conditions for welfare maximization in the social planner's problem are:

$$\frac{dW}{dX_1} = \frac{r}{(X_1+r)^2}\left((v_1+s_1) + \left(\frac{X_2}{X_2+r}(v_2+s_2) - c_2 X_2\right)\right) - c_1 = 0 \qquad (11)$$

$$\frac{dW}{dX_2} = \frac{X_1}{X_1+r}\left(\frac{r}{(X_2+r)^2}(v_2+s_2) - c_2\right) = 0: \qquad (12)$$

Let X_1^S denote the socially optimal investment in basic research and let X_2^S denote the socially optimal investment in product development. The ...rst order conditions determine the socially optimal investments in the two innovations:

$$X_1^S = \sqrt{\frac{r}{c_1}\left((v_1+s_1) + \left(\sqrt{(v_2+s_2)} - \sqrt{rc_2}\right)^2\right)} - r \qquad (13)$$

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$$X_2^S = \sqrt{\frac{r}{c_2}(v_2 + s_2)} - r: \qquad\qquad (14)$$

5.2 Competitive Equilibrium

hurt by the decrease in investment in product development. Depending on which e¤ect dominates, social welfare is increasing or decreasing in the degree of patent protection of basic research . At large degrees of protection of basic research , such that $>\widehat{x_1}$, a marginal increase in the patent protection of basic research decreases welfare, because it decreases the investment in both innovation races.

Using the new notation, the ...rst order condition in (16) can be rewritten as:

$$\frac{dW}{d} = MSB - MSC = 0:\qquad(17)$$

Lemma 1 If the social welfare function $W( )$ has a maximum, it occurs in the interval $<\widehat{x_1}$.

Proof. See Appendix A.5. ■

In view of Lemma 1, hereafter, the analysis of the welfare function and the welfare-maximizing degree of patent protection of basic research focuses on degrees of patent protection , such that $<\widehat{x_1}$.

Lemma 2 The second order condition for welfare maximization with respect to :

$$\frac{d^2W}{d^{\,2}} = \frac{dMSB}{d} - \frac{dMSC}{d}\qquad(18)$$

is negative when $<\widehat{x_1}$, which implies that the welfare function W has a unique maximum in the interval $<\widehat{x_1}$.

Proof. See Appendix A.6. ■

Let $\widehat{w}$ be the implicit solution to (16). Assuming that an interior solution to (16) exists, then $\widehat{w}$ is the welfare-maximizing degree of patent protection of basic research in the competitive equilibrium. If the ...rst order condition in (16) does not have an interior solution, then the welfare-maximizing degree of protection of basic research is a corner solution. This is stated in Proposition 3. Let $\widetilde{v_1}$ be as de...ned in Appendix A.7 and note that $\widetilde{v_1} > rc_1$.

Proposition 3 When $v_1 < \widetilde{v_1}$, the social welfare in the competitive equilibrium increases (decreases) in the degree of patent protection of basic research for $<\widehat{w}$ ($>\widehat{w}$) and achieves a maximum at $=\widehat{w}$, where $0 < \widehat{w} < \widehat{x_1}$. When $v_1 \geq \widetilde{v_1}$, the social welfare in the competitive equilibrium decreases in the degree of patent protection of basic research and is maximized at $= 0$.

Proof. See Appendix A.7. ∎

In other words, when $v_1 < \tilde{v}_1$ the social welfare function has an interior maximum at $\widehat{\alpha}_W$, and when $v_1 \geq \tilde{v}_1$ the social welfare function is maximized at the corner point $\widehat{\alpha}_W = 0$. The meaning of Proposition 3 is that when the monopoly rent from the first innovation, v_1, is small relative to the monopoly rent from the second innovation, v_2, the first innovation should receive patent protection and when the rent from the first innovation, v_1, is large relative to the rent from the second innovation, v_2, the first innovation should not be protected.

Proposition 3 implies that a typical basic innovation with no stand-alone value ($v_1 = 0$) should receive some patent protection. Another implication of Proposition 3 is that, because the welfare-maximizing degree of protection lies in the interval $0 < \widehat{\alpha}_W < \widehat{\alpha}_{X_1}$ and in view of Propositions 1 and 2, basic research firms have an incentive to lobby the government to increase the protection of basic innovations to $\widehat{\alpha}_{X_1}$, and commercial development firms have an incentive to lobby the government that the protection of basic research should be as weak as possible. Figure 3 shows the social welfare function of a typical basic research innovation with $v_1 = 0$ and $s_1 = 0$.

Parameter values: v1=s1=0, v2=s2=1, c1=c2=1, r=.1

$\widehat{\alpha}_W = .5$ $\overline{\alpha}_{X_1} = .89$ α
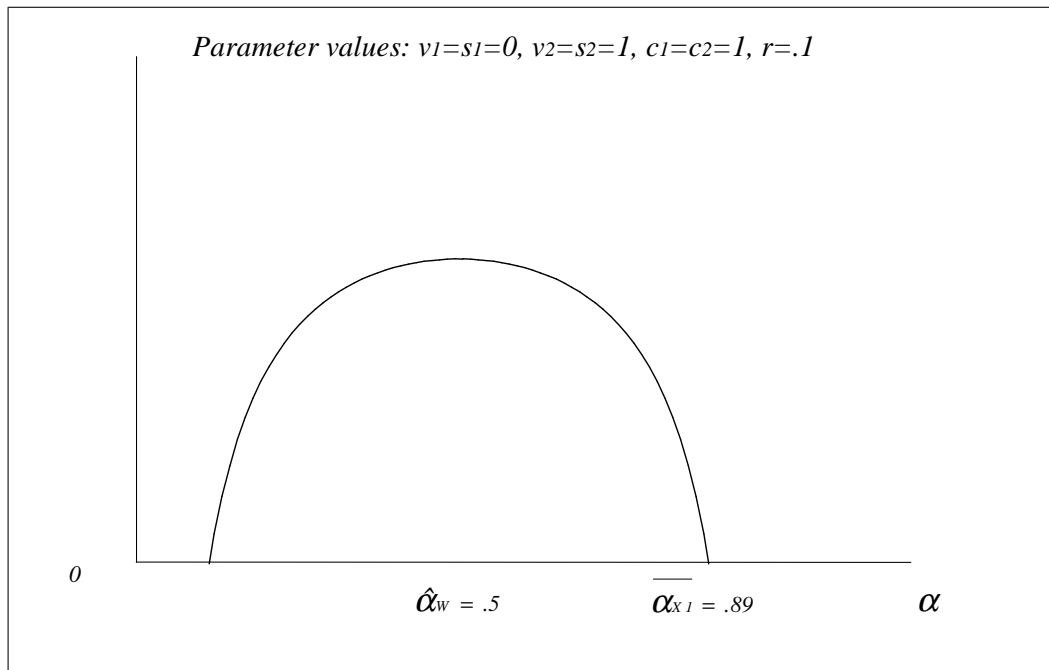
innovation races. I summarize the results in Proposition 4.

Proposition 4 The welfare-maximizing degree of patent protection of basic research $\widehat{w}$ decreases in the monopoly rent from the basic innovation v_1, increases in the consumer surplus from the basic innovation s_1, increases in the marginal cost of the basic research c_1, and decreases in the consumer surplus from the product innovation s_2:

      See Appendix A.8. ∎

    The results in this proposition are intuitive. If the basic innovation has some stand-alone value v_1, then this value provides incentives for investment in basic research in addition to the incentives provided by the tran3

Example In this numerical example I assume a typical basic innovation with no stand-alone value ($v_1 = 0$), which creates no consumer surplus ($s_1 = 0$). The welfare function in (15) simplifies to the expected discounted value of the consumer surplus from the product innovation, $W = \frac{X_1}{X_1+r} \frac{X_2}{X_2+r} s_2$. By solving the first order condition in (16) for , I obtain the welfare-maximizing degree of protection of basic research $\widehat{w} = \frac{\sqrt{c_1}}{\sqrt{c_1}+\sqrt{c_2}}$ (see Appendix A.9).

Note that the welfare-maximizing degree of protection of basic research does not depend on the monopoly rent from the product innovation v_2. This is unlike when the first-stage innovation has some value of its own v_1 and then the welfare-maximizing degree of protection of the first-stage innovation depends on both v_1 and v_2 (see Proposition 4 and the discussion following it). The reason is that there is only one source of monopoly rent (v_2).

Note also that the welfare-maximizing degree of protection of basic research does not depend on the consumer surplus from the product innovation s_2. The reason is that the welfare function simplifies to the expected discounted value of the consumer surplus from the product innovation and then the government's welfare maximization problem is to maximize the probability that the two innovations occur, $\frac{X_1}{(X_1+r)} \frac{X_2}{(X_2+r)}$, which is independent of the actual size of the consumer surplus from the product innovation.

The welfare-maximizing degree of protection of basic research depends only on the marginal costs of innovation at the two stages. In particular, it increases in the marginal cost of basic research c_1, as was stated in Proposition 4. Proposition 4 could not derive analytically the relationship between $\widehat{w}$ and c_2. In this example the welfare-maximizing degree of protection decreases in the marginal cost of product development c_2. The intuition is that when the product development is costly, the protection of basic research should be weak, so that the commercial innovator's share of the product rent can cover the cost of product development.

5.3 Deviations of the Competitive Equilibrium from the Social Optimum

In cumulative innovation there are several known externalities which can cause the investment and the social welfare in the competitive equilibrium to deviate from the social optimum. The first externality arises when the cumulative innovation is not performed within the same firm. Then the first-stage innovation enables the

in Proposition 6 and Proposition 7. Let $\overline{\overline{X_2}}$, $\underline{\underline{X_1}}$ and $\overline{\overline{X_1}}$ be as de..ned in Appendix A.10.

Proposition 6 The aggregate investment in product development in the competitive equilibrium deviates from that in the social planner's problem in the following way: $X_2 \geq X_2^S$ ($X_2 < X_2^S$) when $\leq \overline{\overline{X_2}}$ ($> \overline{\overline{X_2}}$).

Proof. See Appendix A.11. ∎

Proposition 7 The aggregate investment in basic research in the competitive equilibrium deviates from that in the social planner's problem in the following way: $X_1 \geq X_1^S$ when $\underline{\underline{X_1}} \leq \ \leq \overline{\overline{X_1}}$ and $X_1 < X_1^S$ when $< \underline{\underline{X_1}}$ and $> \overline{\overline{X_1}}$:

Proof. See Appendix A.12. ∎

The ..nding in Proposition 6 is intuitive in view of Proposition 1, which states that investment in product development decreases in the degree of patent protection of basic research. Clearly then, overinvestment in product development relative to the social optimum can occur at small degrees of protection of basic research, and underinvestment can occur at large degrees of protection of basic research. Note that if the commercial product creates a very large consumer surplus s_2, then in the competitive equilibrium there is always underinvestment at the second stage relative to the social optimum.

The deviation of the investment in basic research in the competitive equilibrium from the social optimum is more intuitive in light of Proposition 2. Proposition 2 states that the investment in basic research initially increases and then decreases in the degree of protection of basic research. Consequently, at small and at large degrees of patent protection of basic research there is underinvestment in basic research relative to the social optimum, and at intermediate degrees of patent protection of basic research there is overinvestment in basic research in the competitive equilibrium.

Because in general it is not the case that $\overline{\overline{X_2}} = \underline{\underline{X_1}}$ or that $\overline{\overline{X_2}} = \overline{\overline{X_1}}$, the competitive equilibrium cannot yield the socially optimal solution, and therefore the equilibrium investment levels and welfare even under the welfare-maximizing degree of protection of basic research are suboptimal. This con..rms the result in Proposition 5.

6   Conclusions

This paper studies the optimal patent protection of basic research in cumulative innovation. It assumes that the two stages of innovation are basic research and commercial product development, and they are performed by separate firms.

The novelties in this paper are as follows. First, the model in the paper accommodates the specific features of cumulative innovation with basic research at the first stage. Second, the degree of patent protection of basic research is represented by a continuous parameter, which allows systematic analysis of the relationship between the degree of protection of basic research on one side and the R&D investment and the social welfare on the other side. Third, the paper shows that there is no definite answer to the question whether the patent protection of basic research should be weak or strong. The degree of protection depends on the monopoly rents, the marginal costs and the consumer surpluses of the two innovations.

The paper finds that investment in basic research initially increases and then decreases in the degree of patent protection of the basic research, while investment in commercial development always decreases in the degree of protection of the basic research. The first finding differs from that in Denicolo's (2000) model, in which the first-stage investment always increases in the degree of protection of the first-stage innovation. The reason is that Denicolo allows for repeated innovation by the same firm, which is typical for cumulative innovation with product development at the first stage and subsequent product improvement at the second stage.

The paper also finds that the welfare-maximizing degree of protection of basic research decreases in the monopoly rent from the basic innovation, increases in the marginal cost of the basic innovation, increases in the consumer surplus from the basic innovation and decreases in the consumer surplus from the commercial product. The implication for a typical basic innovation with no value of its own is that it should receive stronger protection than a valuable non-basic innovation. Another implication, however, is that because a typical basic innovation does not generate any consumer surplus it should not be protected as much as a first-stage innovation which creates surplus for the consumers.

The paper compares the social welfare in the competitive equilibrium with that in the social planner's problem and finds that it is a second-best. The paper also compares the R&D investment in the competitive equilibrium with the social optimum and finds the following. Basic research firms overinvest (underinvest) relative to

$$\overline{x_1} = \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 + \sqrt{(-v_1 + rc_1 + v_2 - rc_2)^2 + 4v_2(v_1 - rc_1)}\right)$$

$$> \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 + \sqrt{(-v_1 + rc_1 + v_2 - rc_2)^2 + 4(v_2 - rc_2)(v_1 - rc_1)}\right)$$

$$= \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 + \sqrt{(v_1 - rc_1 + v_2 - rc_2)^2}\right)$$

$$= \frac{1}{v_2}(v_2 - rc_2) = \overline{x_2}: \tag{A2}$$

Therefore if $v_1 > rc_1$, then $0 < \quad < \overline{x_2}$ is necessary and sufficient for aggregate investment in both races to be positive.

If $v_1 \leq rc_1$, then

$$\underline{x_1} = \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 - \sqrt{(-v_1 + rc_1 + v_2 - rc_2)^2 + 4v_2(v_1 - rc_1)}\right)$$

$$\geq \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 - \sqrt{(-v_1 + rc_1 + v_2 - rc_2)^2}\right) = 0 \tag{A3}$$

and

$$\overline{x_1} = \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 + \sqrt{(-v_1 + rc_1 + v_2 - rc_2)^2 + 4v_2(v_1 - rc_1)}\right)$$

$$\leq \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 + \sqrt{(-v_1 + rc_1 + v_2 - rc_2)^2 + 4(v_2 - rc_2)(v_1 - rc_1)}\right)$$

$$= \frac{1}{2v_2}\left(-v_1 + rc_1 + v_2 - rc_2 + \sqrt{(v_1 - rc_1 + v_2 - rc_2)^2}\right)$$

$$= \frac{1}{v_2}(v_2 - rc_2) = \overline{x_2}: \tag{A4}$$

Therefore if $v_1 \leq rc_1$, then $\underline{x_1} < \quad < \overline{x_1}$ is necessary and sufficient for aggregate investment in both races to be positive.

Appendix A.3: Proof of Proposition 1.

Proof. Differentiating (4) with respect to

Proof. Differentiating (8) with respect to τ gives:

$$\frac{dX_1}{d\tau} = \frac{(1-\tau)^2 v_2 - rc_2}{(1-\tau)^2 c_1}: \tag{A6}$$

The derivative is positive (negative) when $\tau < 1 - \sqrt{\frac{rc_2}{v_2}}$ ($\tau > 1 - \sqrt{\frac{rc_2}{v_2}}$) and equal to zero when $\tau = 1 - \sqrt{\frac{rc_2}{v_2}}$. ∎

Appendix A.5: Proof of Lemma 1.

Proof. It follows directly from Proposition 1 and Proposition 2 that when $\tau \geq \widehat{\tau}_{X_1}$, then $MSB \leq 0$ and $MSC > 0$, and therefore $\frac{dW}{d\tau} < 0$. Therefore if the social welfare function achieves a maximum, it has to occur for $\tau < \widehat{\tau}_{X_1}$. ∎

Appendix A.6: Proof of Lemma 2.

Proof. The second order condition for welfare maximization with respect to τ in (18) is:

$$\frac{d^2W}{d\tau^2} = \frac{dMSB}{d\tau} - \frac{dMSC}{d\tau}:$$

To show that when $\tau < \widehat{\tau}_{X_1}$, then $\frac{d^2W}{d\tau^2} < 0$, it is sufficient to show that when $\tau < \widehat{\tau}_{X_1}$, then $\frac{dMSB}{d\tau} < 0$ and $\frac{dMSC}{d\tau} > 0$.

The derivative of MSB with respect to τ is :

$$\frac{dMSB}{d\tau} = \frac{r^2 s_2 \frac{dX_1}{d\tau}\frac{dX_2}{d\tau}}{(X_1+r)^2(X_2+r)^2} \tag{A7}$$
$$+ \frac{r\left(s_1(X_2+r)+s_2 X_2\right)\left((X_1+r)\frac{d}{d\tau}\left(\frac{dX_1}{d\tau}\right)-2\left(\frac{dX_1}{d\tau}\right)^2\right)}{(X_1+r)^3(X_2+r)}:$$

When $\tau < \widehat{\tau}_{X_1}$, the first term in (A7) is negative because $\frac{dX_1}{d\tau} > 0$ by Proposition 2 and $\frac{dX_2}{d\tau} < 0$ by Proposition 1. When $\tau < \widehat{\tau}_{X_1}$, the second term is negative because $\frac{d}{d\tau}\left(\frac{dX_1}{d\tau}\right) = -\frac{2rc_2}{(1-\tau)^3 c_1} < 0$. Therefore, when $\tau < \widehat{\tau}_{X_1}$, then $\frac{dMSB}{d\tau} < 0$.

The derivative of MSC with respect to τ is:

$$\frac{dMSC}{d\tau} = \frac{-r^2 s_2 \frac{dX_1}{d\tau}\frac{dX_2}{d\tau}}{(X_1+r)^2(X_2+r)^2} \tag{A8}$$
$$+ \frac{-rs_2 X_1\left((X_2+r)\frac{d}{d\tau}\left(\frac{dX_2}{d\tau}\right)-2\left(\frac{dX_2}{d\tau}\right)^2\right)}{(X_1+r)(X_2+r)^3}:$$

When $\tau < \widehat{\tau}_{X_1}$, the first term in (A8) is positive because $\frac{dX_1}{d\tau} > 0$ by Proposition 2 and $\frac{dX_2}{d\tau} < 0$ by Proposition 1. When $\tau < \widehat{\tau}_{X_1}$, the second term is positive because $\frac{d}{d\tau}\left(\frac{dX_2}{d\tau}\right) = 0$. Therefore, when $\tau < \widehat{\tau}_{X_1}$, then $\frac{dMSC}{d\tau} > 0$. ∎

Appendix A.7: Proof of Proposition 3.

Proof. Recall that by Assumption 2 feasible degrees of protection of basic research are:

$$0 \leq \quad < \overline{x_2} \text{ when } v_1 > rc_1 \text{ and}$$
$$\underline{x_1} < \quad < \overline{x_1} \text{ when } v_1 \leq rc_1:$$

Assuming that an interior solution to the ...rst order condition of the government's welfare maximization problem in (16) exists, that is assuming that $\widehat{w}$ is among the feasible degrees of protection of basic research de...ned in Assumption 2, it follows from Lemma 1 and from the negativity of the second order condition for welfare maximization when $< \widehat{x_1}$ that social welfare increases (decreases) in the degree of patent protection of basic research for $< \widehat{w}$ ($> \widehat{w}$) and achieves a maximum at $= \widehat{w}$, where $\widehat{w} < \widehat{x_1}$.

Next, I examine whether the government's welfare maximization problem may have a corner solution. A corner solution would occur if the solution to the ...rst order condition in (16), $\widehat{w}$, lies outside the range of feasible degrees of protection of basic research . It follows from Lemma 1, that the welfare-maximizing degree of protection of basic research $\widehat{w}$ occurs in the interval $< \widehat{x_1}$ and therefore a corner solution cannot occur at either of the upper bounds on the feasible degree of protection of basic research ($\overline{x_2}$ when $v_1 > rc_1$ and $\overline{x_1}$ when $v_1 \leq rc_1$). I then examine whether a corner solution can occur at the lower bounds on the feasible degree of protection of basic research (0 when $v_1 > rc_1$ and $\underline{x_1}$ when $v_1 \leq rc_1$). A corner solution would occur at $= 0$ if $\widehat{w} < 0$ when $v_1 > rc_1$ and then $\frac{dW}{d} \mid_{=0} \leq 0$. A corner solution would occur at $= \underline{x_1}$ if $\widehat{w} < \underline{x_1}$ when $v_1 \leq rc_1$ and then $\frac{dW}{d} \mid_{=\underline{x_1}} \leq 0$. Thus to ...nd out whether corner solutions exist at the lower bounds it is su¢ cient to check whether $\frac{dW}{d} \mid_{=0} \leq 0$ or $\frac{dW}{d}$

Thus, when $v_1 \geq \tilde{v}_1$, the government's welfare maximization problem has a corner solution at $\quad = 0$.

Second, when $v_1 \leq rc_1$, the ..rst order condition in (16) evaluated at the lower bound on the feasible degree of protection of basic research, $\underline{x_1}$, and simpli..ed is:

$$\frac{dW}{d} \Big|_{=\underline{x_1}} = \frac{r\frac{\left((1-\ )^2 v_2 - rc_2\right)}{c_1(1-\ )^2}\left(s_1\left(X_2 + r\right) + s_2 X_2\right)}{\left(X_1 + r\right)^2\left(X_2 + r\right)};$$

which is positive because $(1 - \ )^2 v_2 - rc_2 > 0$ by Assumption 1. Thus, the government's welfare maximization problem does not have a corner solution at $\quad = \underline{x_1}$.

∎

Appendix A.8: Proof of Proposition 4.

Proof. To determine the sign of $\frac{d d_W}{d v_1}$

Appendix A.9: Derivation of $\widehat{w}$ when $v_1 = s_1 = 0$.

Substituting with the equilibrium values of X_1 and X_2 in the ..rst order condition for welfare maximization in (16), and using the fact that $v_1 = s_1 = 0$, gives:

$$\frac{dW}{d} = \frac{rs_2 \left((1-\ )^2 c_1 - \ ^2 c_2\right)}{\ ^2 (1-\ )^2 v_2} = 0:$$

The solution to that ..rst order condition is $\widehat{w} = \frac{\sqrt{c_1}}{(\sqrt{c_1}+\sqrt{c_2})}$.

Appendix A.10: De..nitions of $\overline{\overline{X_2}}$, $\underline{\underline{X_1}}$ and $\overline{\overline{X_1}}$.

Let $\overline{\overline{X_2}} = 1 - \frac{\sqrt{rc_2(v_2+s_2)}}{v_2}$.

Let $\underline{\underline{X_1}} = \frac{(v_2-rc_2+A)-\sqrt{(v_2-rc_2+A)^2-4v_2A}}{2v_2}$ and $\overline{\overline{X_1}} = \frac{(v_2-rc_2+A)+\sqrt{(v_2-rc_2+A)^2-4v_2A}}{2v_2}$,

with $A = \sqrt{rc_1 \left(v_1 + s_1 + \left(\sqrt{v_2 + s_2} - \sqrt{rc_2}\right)^2\right)} - v_1$.

Appendix A.11: Proof of Proposition 5.

Proof. The result in the proposition follows from comparing the aggregate investment in product development in (4) and (14). ∎

Appendix A.12: Proof of Proposition 6.

Proof. The result in the proposition follows from comparing the aggregate investment in basic research in (8) and (13). ∎

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