The Role of Patents for Bridging the Science to Market Gap

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Abstract

This paper examines an ex-post rationale for the patenting of scientific discoveries. In this model, scientist do not know which firms can make use of their discoveries, and firms do not know which scientific discoveries might be useful to them. To bridge this gap, either or both sides need to engage in costly search activities. Patents determine the appropriability of scientific discoveries, which affects the scientists' and firms' willingness to engage in search. Patents increase (decrease) dissemination when scientists' (firms') search is sufficiently elastic. The model also examines the role of universities. Patents facilitate the delegation of search activities to the universities' technology transfer offices, which enables efficient specialization. Rather than distracting scientists from doing research, patenting may be a complement to doing research.

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1 Introduction

Over the last few decades, the number of patents filed by university scientists has increased dramatically (Jaffee, 2000, Gallini, 2002). In the US, an important driver for this has been the Bayh-Dole act. Given the central role that science plays in the development of new technologies, it is important to ask what effect the patenting of scientific discoveries is likely to have.

Standard economic theory emphasizes the incentive effects of patents. In order to be willing to invest in research and development, it is necessary to have a guarantee that the intellectual property generated by the investment is adequately protected against appropriation. A large theoretical literature has closely studied this rationale (Gallini and Scotchmer, 2001). The empirical evidence is sometimes inconclusive, but provides at least some support for an incentive effect of patents (Arora, Ceccagnoli and Cohen, 2004, Cohen et. al. 2002, Levin et. al., 1987). While the incentive rationale is reasonably persuasive for private sector R&D, its applicability to academic research is more questionable: scientists did research long before patents existed; scientists are often intrinsically motivated (Murdock, 2002, Stern 2004) and concerned about academic freedom (Aghion, Dewatripont and Stein, 2005); and scientists' incentives are strongly affected alternative incentive systems, such as tenure (Carmichael, 1988). The effect of patents on scientists' effort to engage in research are likely to be small. If anything, the argument has been made that patenting can become a distraction to scientists: they may divert research from basic to applied fields, and they may temp scientists to pursue private profits opportunities, through start-ups or industry collaborations (Shane, 2004a).

Apart from the ex-ante incentive argument, a small number of economists have argued that patents also play an ex-post role. Patents encourage the dissemination of scientific knowledge, after the discovery has already been made. This argument dates back to Kitch (1977). An important aspect is that there is a long path from scientific discovery to marketable new product.[1] The scientific discovery is only one of several inputs in a risky development process, that hopefully leads to the eventual introduction a new product. A further complication is that the scientist's tacit knowledge (or "know-how") may be an important, sometimes even indispensable input for the development process.

If scientific discoveries are merely intermediate products, we have to distinguish two distinct scenario. In one scenario the final product is not patentable, nor can it be protected by other means such as complementary assets or secrecy. In this case it is easy to see that patents for scientific discoveries are valuable. They solve the appropriability problem at the input level, when it cannot be solved at the final product level. Naturally, one has to ask why it is that only inputs but not outputs can be patented. We focus on the other scenario where the final product can be

[1] Our discussion here will focus mostly on product patents, although the argument is similar for process patents.

patented, or protected by other means. In this case, allowing "input" patents for scientific discoveries allocates the intellectual property to the scientists, while allowing only "output" patents allocates the intellectual property to the firms that develop the products. Under the Coase theorem, different patent allocations only affect the distribution of rents, but not the outcome or efficiency of the development process. Naturally, the Coase theorem assumes efficient contracting. If all that is required is that a specific scientist and a specific firm agree on the terms of a development contract, then he Coase theorem seems appropriate.

In this paper we identify a fundamental problem that prevents efficient Coasian contracting. Scientists often do not know what the potential uses of their scientific discoveries are, and they do not know what firms may be potentially interested. Similarly, firms are often unaware of what scientific discoveries may be valuable for them. This is what we call the gap between science and the market. The process of commercialization has (at least) two important stages: there is the development stage, where the scientist and the firm need to combine their knowledge and assets to attempt commercial development. At this stage, efficient contracting may be possible. Prior to the development stage, however, there is a search stage, where a match has to be found between a scientific discovery and a firm that can potentially make use of it. Elfenbein (2005) shows that considerable time and effort are required to identify firms that are willing to license intellectual property from universities. At this stage, there cannot be efficient contracting between the scientist and the firm, simply because they have not met yet. Hence the Coase theorem does not apply, and the allocation of intellectual property rights matters for outcomes. This is the starting point of our analysis for an ex-post rationale of patenting scientific discoveries.

A typical economic argument might go as follows. Consider a scientist who has made a discovery that no one knows about. The scientist can invest some time and money into promoting her discovery, searching for an appropriate firm that can use the discovery for the development of some new product. Without patent protection, when the scientist discloses the discovery to the firm, the firm can appropriate the discovery. This ruins the scientist's incentives to seek out firms in the first place. As a result, the discovery remains unused. Patent protection can change this sad state of affairs, since it allows the scientist to collect a licensing fee for her discovery. Thus, patents motivate scientists to promote their discoveries.

Though simple and elegant, this argument is also incomplete. It assumes a one-sided matching process, where scientists seek out firms to promote their scientific discoveries. Presumably these discoveries constitute technological "solutions." The scientists' challenge is to find a suitable "problem," i.e., a market need that can be addressed with their scientific discoveries. It might be more efficient to have problems seeking solutions, rather than solutions seeking problems. Consider the following quote from an MIT engineer (Shane (2004b), p. 204):

> With university technologies you pull the technology out and you run around saying 'Where can it stick?' It's probably much better to say I've

> heard about these problems and I think I can solve it. But with companies coming out of MIT, it's always the same thing, what do I do with it to shoehorn it back into industry?

Naturally, firms realize that they can do better than merely wait for scientists to find them. Indeed, there is a literature on firm's absorptive capabilities, that argues that firms invest in research capabilities, in order to find what scientific discoveries might suit their needs (Cohen and Levinthal, 1989).

In this paper we develop a formal theory of the search and matching process between scientists and firms. The model allows us to address the role of patents in bridging the science to market gap. We do not rely on traditional incentive theories for the generation of new ideas, and therefore take the arrival rate of scientific discoveries as given (Section 5.1 shows how the model can be augmented to include ex-ante incentives). We assume that most discoveries are irrelevant for most firms, but that occasionally there is a match between a scientist and a firm. To find a match, firms and scientists invest in search. We use the term search in a broad sense. For a scientist, this includes promoting her discoveries, and making them more accessible to non-scientists. For a firm, this includes investing in absorptive capabilities (e.g. hiring managers who's role it is to interact with academia), and communicating its own technological needs. A match means that the firm has complementary assets to pursue a development project that is based on the scientist's discovery. The model allows the scientist to have some tacit knowledge, that improves the odds of success for the development process.

In the absence of patents, the firm can appropriate most the value from the discovery. The only source of bargaining power the scientist has stems from her tacit knowledge. In equilibrium, the firm appropriates the idea, but agrees to a consulting contract, that rewards the scientist for her continued involvement with the development process. With patents, the scientist is in a much stronger bargaining position. In equilibrium the firm pays both for the patent and the tacit knowledge.

In a one-sided search model, where scientists promote their ideas to firms, but not vice versa, we find that patents always increase scientists' search incentives, and thus reduce the expected time to find a match. This conclusion is easily reversed in a two-sided search model, where patents promote scientists' search, but discourage firms' search. The net effect of patenting depends on the relative search efficiencies of the two parties. In the model, we also show that if there are complementarities in search - this happens, for example, if scientists can only be found if they are actively searching themselves - then there are multiple equilibria. In fact, there always exists one equilibrium where the market collapses, because each side of the market waits for the other to make themselves visible. These results add to the debate about the economic role of patents. Much of the debate has focused on the ex-ante incentives to generate innovations. Our emphasis on ex-post rationales complements this debate, providing arguments both for and against patenting.

So far, our discussion makes the simplifying assumption that only two parties are involved, scientists and firms. In reality, there is a third player that matters, namely the university. In most cases the university, not the scientist, owns the patent. The university's technology transfer office can also assume the role of an intermediary between scientists and firms.

We augment our base model by introducing the university's technology transfer office as a third player. We assume that its objective function is to maximize the university's returns. Any development contract is now negotiated between three parties. The technology transfer office has a lower cost of search, because of specialization and/or because of a lower opportunity cost of time. The interesting question is whether or not the scientist wants to delegate the search activities to the technology transfer office. It turns out that this critically depends on whether the scientist and the technology transfer office can write complete contracts, at the beginning of the search process. If such contracts are hard to write, then we obtain the interesting result that with patent protection, the scientist gladly delegates all search activities to the technology transfer office. Without patent protection, however, the technology transfer office has no incentives to search for firms. In this case the scientist prefers to take responsibility of the search process herself. A complete contract prevents this breakdown in delegation. However, writing a complete contract might be challenging, because, without a patent, it is difficult to verify what constitutes a transfer of intellectual property.

This result about delegation is reminiscent of the historic origins of the US patent system. Lamoreaux and Sokolow (1999, 2001) show that the development of patents in nineteenth century US was largely driven by the activities of patent intermediaries, who specialized in the geographic dissemination of innovations. The result on delegation also has implication for the debate whether patents encourage or discourage basic research. After carefully controlling for selection effects, Azoulay, Ding and Stuart (2005) find that patenting increases research productivity. This paper provides a novel interpretation for this result, one that does not depend on effort incentives. Patents allow scientists to delegate the promotion of their scientific discoveries. This frees up their time to continue pursuing their research. To the extent that the technology transfer office succeeds in finding interested firms, however, scientists may end up also spending some time consulting. Consistent with this, Azoulay, Ding and Stuart find that scientists who patent, are subsequently more likely to coauthor with authors in industry.

The paper is structured as follows. Section 2 lays out the base model. Section 3 derives the results for the one-side and two-sided search model. Section 4 introduces the university's technology transfer office as a third party. Section 5 discusses a variety of model extensions. It is followed by a brief conclusion.

2 Base model

2.1 Base assumptions

All parties are risk-neutral. There is an infinite horizon, and we focus on steady state equilibria. Let Δ be the length of any one period. We focus mostly on the continuous time case, where $\Delta \to 0$. All parties use a discount rate $r\Delta$.

Suppose there is a number of scientists who all have a single scientific discovery. Each period, a discovery becomes obsolete with probability $\delta\Delta$. Each period, there are $s\Delta$ new scientists arriving with a new discovery. We assume that s is exogenous. This assumption means that we are ignoring any incentive effects on the scientific discovery process itself. Section 5.1 return to this issue. On its own, a scientific discovery cannot generate commercial value.[2] Such value can only be created as part of a development project with a firm that has complementary assets. We assume that firms are infinitely lived. For simplicity we assume that the number of firms is fixed. We relax this in section 5.1.

Consider the issue of fit between scientific discoveries and firms. Most discoveries are irrelevant to most firms. However, there are some matches between discoveries and firms that constitute development opportunities. If there is a match between a scientific discovery and a firm, there is the additional question of what role the scientist plays. We allow for the fact that the scientist has some tacit knowledge that makes it worthwhile to involve her in the development process. Throughout the paper we use the subscripts S and F respectively for scientists and firms. The costs of development are given by d_F and d_S. Let p denoted the probability that development results in a usable innovation of value of x. With probability $1 - p$, nothing valuable comes out of development. We denote the expected return from development by $\pi = px - d_F - d_S$. We assume that if one firm invests in developing a discovery, no other firm wants to compete with it. If the scientist refuses to be involved in the development process, the firm may still try to develop the discovery. Using obvious notation, we denote the expected return from noncooperative development by $\pi_0 = p_0 x_0 - d_{F,0}$. We focus on the case where the involvement of the scientist is efficient, i.e., $\pi \geq \pi_0$.[3]

Central to the analysis is the comparison between the regimes where the scientific discovery is or is not protected by patents. For this we assume that the existence of patents does not affect the value of x. We can think of the regime without patents as a regime where there is no patent protection for scientific discoveries, but there is patent

[2]It is trivial to extend the model to allow the discovery to still have some value without the development by another firm. For example, the scientist might attempt to develop the discovery by herself. All that matters for the model is that search and subsequent development by another firm is more efficient.

[3]The analysis for $\pi < \pi_0$ is straightforward. If the scientist adds no value, the exact value of π is irrelevant, since it affect neither equilibrium outcomes nor outside options. The model with $\pi < \pi_0$ thus yields the same utilities as with $\pi = \pi_0$.

protection for the innovations that firms create on the basis of scientific discoveries. Alternatively, firm innovations may be naturally protected by complementary assets or other competitive advantages. In section 5.3 we also examine an extension where patent protection is imperfect.

The game consists of two main stages. At the initial search stage (which is played out in continuous time) scientists and firms incur search costs. If a discovery becomes obsolete, the game simply ends for that scientist. If there is a match between a discovery and a firm, the game progresses to the development stage. We denote the utilities at the beginning of the development stage by u_F and u_S. The utilities at the beginning of the search stage are denoted by U_F and U_S.

When a firm engages in development, the scientist receives a transfer α. At the beginning of the development process, the respective utilities are given by $u_F = \pi - \alpha$ and $u_S = \alpha$. Below we derive the equilibrium value of α. α includes the consulting fees, and possibly a payment for the intellectual property. In this simple model, it does not matter whether the transfer α is unconditional (such as a licensing fee), or conditional upon success (such as a royalty fee, profit-share, or equity stake).[4]

Central to the model is the matching process by which firms and scientists find each other. The probability that a given scientist finds a matching firm, is different from the hazard that a given firm finds a matching scientist, simply because there are different number of scientists and firms. Let $e_S\Delta$ be the probability that a specific scientist finds a specific firm in any one period. And let $e_F\Delta$ be the probability that a specific firm finds a specific scientist in any one period. We assume that all these probabilities are independent. Section 5.4 relaxes this assumption. For Δ sufficiently small, we can ignore all probabilities that multiple matches occur in the same period.[5]

The number of scientists and firms is denoted by n_S and n_F. The probability that a specific scientist finds some firm with complementary assets is given by $n_F e_S \Delta$, and the probability that she is found by some firm with complementary assets is given by $n_F e_F \Delta$. Define

$$m_S = n_F e \text{ and } m_F = n_S e \text{ where } e = e_F + e_S, \tag{1}$$

then the probability that a specific scientist finds a match in period t is simply given by $m_S\Delta$. Note that e represents the (instantaneous) probability that a match occurs between a specific scientist and firm. Using analogous reasoning, the probability that a specific firm finds a match in period t is simply given by $m_F\Delta$.

Finding a match requires costly search efforts. The search intensities e_S and e_F are private non-contractible choices. The per-period cost of search is given by Δc_S, where we assume standard convex search costs: $c_S(e_S)$ satisfies $c_S' > 0$, $c_S'' > 0$ and $c_S(0) = 0$; similar for $c_F(e_F)$.

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[4] To elaborate, let a be the unconditional and A the conditional transfer, then $\alpha = a + pA$. It is easy to see that if the scientist's development contribution is non-contractible, then incentive-compatibility requires that $pA - d_S \geq p_0 A \ \Leftrightarrow A \geq \dfrac{d_S}{p - p_0}$.

[5] These probabilities are all of the order Δ^2 or higher, and naturally vanish for $\Delta \to 0$.

We denote the utility of a scientist in period t by $U_S(t)$. This is given by

$$U_S(t) = m_S(t)\Delta u_S(t) + (1 - m_S(t)\Delta - \delta\Delta)\frac{1}{1+r\Delta}U_S(t+\Delta) - c_S(t)\Delta$$

In a steady state equilibrium we obtain after simple transformations $U_S = \frac{1+r\Delta}{r+\delta+m_S}[m_S u_S - c_S]$. For $\Delta \to 0$ we obtain

$$U_S = \frac{m_S u_S - c_S}{r+\delta+m_S} \quad (2)$$

The utility of a firm is thus given by

$$U_F(t) = m_F(t)\Delta u_F(t) + \frac{1}{1+r\Delta}U_F(t+\Delta) - c_F(t)\Delta$$

In steady state with $\Delta \to 0$ we get

$$U_F = \frac{m_F u_F - c_F}{r} \quad (3)$$

Note that U_S and U_F have different denominators. This is because they have different time horizons. Scientists have a single idea and then exit the market. In contrast, firms participate in the market all the time, and develop all good ideas that they can find.

The number of scientists is obtained from $n_S(t+\Delta) = n_S(t)(1-\delta\Delta-m_S\Delta)+s\Delta$. In steady state, we obtain $n_S = s\frac{1-m_S\Delta-\delta\Delta}{\delta+m_S}$, which for $\Delta \to 0$ yields

$$n_S = \frac{s}{\delta+m_S}. \quad (4)$$

The number of scientists searching for firms is larger, if there are many new discoveries (high s), little obsolescence (low δ) and few successful matches (m_S).

2.2 Bargaining game

We assume that all bargaining follows the Nash bargaining solution (Binmore, Rubinstein and Wolinsky, 1986).

If a scientist does not have a patent, the first firm with complementary assets can appropriate the discovery and develop it by itself.[6] The only source of bargaining power for the scientist comes from her tacit knowledge, that can increase the expected value of development. The Nash bargaining solution immediately implies

[6] In this model we assume that the scientist discloses the information only after she can ascertain that the firm is a potential match. Hellmann and Perotti (2005) examine a model where an idea generator cannot distinguish between partners that are complements or substitutes. In such a model, an idea may circulate among several agents before an appropriate match is found.

$$u_F^N = \frac{\pi + \pi_0}{2} \text{ and } u_S^N = \frac{\pi - \pi_0}{2} \ . \tag{5}$$

The superscript N refers to the no patenting regime. We use this superscript only when there is a potential confusion with the other regime where there are patents, which we refer to with the superscript P.

Consider now the case where patent protection holds. Suppose a scientist has disclosed the idea to a firm with complementary assets. The firm's outside option is simply to forgo the opportunity, which yields zero utility. The scientists outside option is to search for another firm. This effectively means starting all over again. It therefore yields the same utility as next period's ex-ante utility $\frac{1-\delta\Delta}{1+r\Delta}U_S$. Using $\Delta \to 0$, we obtain the following Nash values

$$u_S = \frac{\pi + U_S}{2} \text{ and } u_F = \frac{\pi - U_S}{2}.$$

Note that π_0 does not enter these expressions. This is because developing the discovery without the scientist is no longer an option when the scientist controls the intellectual property. Using $U_S = \frac{m_S u_S - c_S}{r + \delta + m_S}$ we obtain after standard transformations

$$u_F^P = \frac{\pi(r+\delta) + c_S}{2(r+\delta) + m_S} \text{ and } u_S^P = \frac{\pi(r+\delta+m_S) - c_S}{2(r+\delta)+m_S} \tag{6}$$

Intuitively, the higher the scientist's search cost (c_S), the weaker her bargaining power. Moreover, the higher the discount rate (r) or obsolescence rate (δ), the weaker the scientist's bargaining power.[7]

3 Results from the base model

3.1 One-sided search

We first solve the one-sided model, where only scientists search for firms. This model assumes $e_F = 0$. Every period the scientist maximizes $U_S(t)$ with her optimal choice of $e_S(t)$. The first-order condition is given by $\frac{dm_S(t)}{de_S}[u_S(t) - \frac{1-\delta\Delta}{1+r\Delta}U_S(t+\Delta)]\Delta - c'_S(t)\Delta = 0$. Using $\frac{dm_S(t)}{de_S} = n_F$ we get

[7] We note that $\frac{du_S^P}{dr} \sim \frac{du_S^P}{d\delta} \sim (2c_S - m_S\pi) < 0$. To see that this is negative, we simply note that $U_S = \frac{m_S\frac{\pi+U_S}{2} - c_S}{r+\delta+m_S} > 0 \Leftrightarrow m_S\frac{\pi}{2} - c_S = U_S(r+\delta+\frac{m_S}{2}) > 0$.

$$n_F[u_S(t) - \frac{1-\delta\Delta}{1+r\Delta}U_S(t+\Delta)] - c_S'(t) = 0.$$

The first term captures the marginal benefit while the second the marginal cost. The marginal benefit naturally scales with the number of firms n_F. The most interesting term is $u_S(t) - \frac{1-\delta\Delta}{1+r\Delta}U_S(t+\Delta)$. This measures the difference in utilities between finding a partner now, versus not finding one now and continuing to look for one.

For the steady state, using $\Delta \to 0$, we rewrite the first order condition as

$$n_F(u_S - U_S) - c_S' = 0. \tag{7}$$

Proposition 1 *In the one-sided search model, the effect of patent protection is to increase the scientists' search intensity (e_S).*

The proof is in the appendix. The intuition for Proposition 1 is straightforward. Patent protection increases the rents that scientists can capture from their scientific discoveries. This gives them a greater incentive to seek out firms that may be able to develop these scientific discoveries. Indeed, without patent protection, the only incentive that scientists have is to obtain a consulting contract. With a patent, they are also looking at the return of their intellectual property.

In steady state, the likelihood of finding a match is constant. This implies that the time it takes to find a match (or become obsolete) has a negative exponential distribution, with an expected waiting time of $\frac{1}{\delta + m_S}$. This is decreasing in e_S, which implies that patenting reduces the expected waiting time. Patenting also reduces the number of scientists actively searching, since n_S is decreasing in e_S (see equation (4)).

Another interesting aspect of the model concerns preferences over patent protection. Scientists always prefer to have patent protection. In most cases, firms would prefer it if scientists have no patent protection, since this increases their value of development from $u_F^P = \frac{\pi - U_S}{2}$ to $u_F^N = \frac{\pi + \pi_0}{2}$. However, there is a possibility that firms too prefer patent protection. This is because patent protection increases the number of matches.[8]

3.2 Two-sided search

The model with two-sided search is analogous to the one-sided model, except that scientists and firms make simultaneous search decisions. The firm maximizes by $U_F(t)$

[8] For example, in the absence of patent protection, for $\pi_0 \to \pi$ we get $u_S \to 0$; equation (7) implies $e_S \to 0$, and thus $U_F^N \to 0$. Under these circumstances, the lack of patent protection leads to a market failure, that hurts not only scientists, but also firms. More generally, we note that the utility frontier between firms and agents is analogous to that of a standard principal-agent model. A well-known result is that principals sometimes want to pay information rents (or "efficiency wages") to agents, in order to move out of any backward-bending part of the utility frontier. The same applies here, except that patents must be used instead of wages.

choice of $e_F(t)$. The first order condition is given by $\frac{dm_F(t)}{de_F}\Delta u_F(t) - c_F'(t)\Delta = 0$. For $\Delta \to 0$ and using $\frac{dm_F(t)}{de_F} = n_S$ we get

$$n_S u_F - c_F' = 0. \tag{8}$$

Note that while scientists promote a single idea, firms are always looking for ideas. That explains why their marginal incentive is not affected by concerns of urgency. Indeed, the optimal choice of e_F does not depend directly on r or δ (although there may be an indirect effect through u_F).

To determine the steady state equilibrium, we also need to consider the endogenously determined number of scientist. That is, equations (4), (7) and (8) determine the equilibrium values of n_S, e_S and e_F. We reduce this to a system of two equations by using (4) in (8). Furthermore, we use (2) to obtain $u_S - U_S = \frac{(r+\delta)u_S + c_S}{r+\delta+n_F(e_S+e_F)}$. We can therefore rewrite the two equilibrium conditions as

$$n_F \frac{(r+\delta)u_S + c_S}{r+\delta+n_F(e_S+e_F)} - c_S' = 0 \text{ and } \frac{s u_F}{\delta + n_F(e_F+e_S)} - c_F' = 0. \tag{9}$$

These two condition describe the steady state reaction functions of scientists and firms. The first term describes the marginal benefit of increasing search, the second the marginal cost. We note that e_S and e_F are strategic substitutes: a higher value of e_F reduces the marginal benefit of increasing e_S, and a higher value of e_S reduces the marginal benefit of increasing e_F.[9]

The effect of patent protection is to increase u_S and reduce u_F. This increases the scientists' marginal benefit, whilst reducing the firms' marginal benefit. We thus obtain the following result.

Proposition 2 *In the two-sided search model, the effect of patent protection is to increase the scientists' search intensity (e_S), but to decrease the firms' search intensity (e_F). The effect on the total search intensity ($e = e_F + e_S$) is ambiguous. If the scientists' search behavior is sufficiently inelastic (i.e., c_S'' is sufficiently large), then patent protection reduces e.*

The proof is in the appendix. Proposition 2 shows that in a two-sided model, the net effect of patenting is ambiguous. On the one hand it encourages scientists' search, on the other it discourages firms' search. Whether or not patenting increases the total

[9] It is interesting to note that while the steady state reaction functions are substitutes, the instantaneous reaction functions are independent. To see this, we note from the instantaneous first-order condition that the choice of $e_F(t)$ does not depend on $e_S(t)$. Similarly, $e_S(t)$ does not depend on the contemporaneous value of $e_F(t)$, even though it does depend on all future values of $e_F(t+i\Delta)$ ($i = 1, 2, ...$) through $U_S(t+\Delta)$. This shows that the instantaneous reaction functions are independent. It also guarantees that both scientist and firms have a unique optimal choice.

probability of a match (e) - and thus decreases expected the waiting time ($\frac{1}{m_S}$), as well as the number of scientists actively searching (n_S) - depends on the relative search elasticities. If scientists respond relatively little to higher expected payoffs (relative to the response of firms), then patenting fails to increase dissemination, as measured by the probability of finding a match (e). The scientists' response is inelastic if c_S'' is large, i.e., if marginal search costs are sufficiently steep.

For the one-sided model we noted that if scientists' search incentives are important, then it is possible that not only scientists, but firms too, would prefer that discoveries can be patented. A symmetrical argument can be made that if firms' search incentives are important. In this case, it is possible that not only firms, but scientists too, would prefer that discoveries cannot be patented. This is because patenting reduces firms' incentives, which may excessively discourage their search intensity.

4 The role of the technology transfer office

So far the analysis makes the simplifying assumption that scientists own the patents, and that they search for firms by themselves. We now consider a richer and more realistic set-up, where there is a third player, namely the university's technology transfer office (TTO henceforth). In most cases, it is the university, not the scientist, that owns the patent. Broadly speaking, this is true whenever the scientific discoveries were obtained making use of university resources. The role of the TTO is to administer the university's patent portfolio, as well as to provide some intermediation services for the transfer of technology. Concretely, the TTO performs a variety of tasks. It often takes care of administrative steps, such as the filing of patents. It negotiates with the scientist. Even though the university owns the patent, the TTO may still share the rewards with the scientist, especially if her participation is required at the development stage. Moreover, the TTO may take over the process of identifying firms interested in developing the technology. That is, in many cases, it is not so much the scientist as the TTO that engages in the search activities we have described so far.

The objective of this paper is not to model all the intricacies of how a TTO operates, but, more specifically, to examine how the presence of a TTO affects the matching process between scientific discoveries and firms. To achieve this objective, we have to make a number of modelling choices. It is likely that a TTO has a comparative advantage at identifying potential partner firms. This is because it can hire managers who specialize in that task, and who do not have the competing time pressures of pursuing scientific research itself. Using obvious notation, we assume that the TTO has search costs $c_T(e_T)$ (again with $c_T(0) = 0$, $c_T' > 0$ and $c_T'' > 0$), such that $c_T' < c_S'$ for all $e_T = e_S$. Moreover, we assume that e_S and e_T are duplicative, so that either the scientist or the TTO would want to search, but not both.

One obvious advantage of having a TTO is that it probably makes it easier for firms to find scientific discoveries. That is, the presence of a centralized office that provides information on research activities facilitates firms' search. This is likely to reduce c_F.

In the neoclassical tradition of presuming selfish economic behavior, we assume that the TTO maximizes the returns of its owner, which is the university. Thus, the TTO equates the university's marginal benefits of finding a match with its marginal cost of searching. It does not take into account any benefits to the scientist, let alone to potential partner firms.[10]

At the time of negotiating the development contract, there are now three parties at the bargaining table: the firm who has the complementary asset, the scientist who might have some valuable tacit knowledge, and the TTO who owns the patent (if there is one). We assume that the three parties divide the returns according to the Shapley solution (Hart and Mas-Collel, 1986).

Another modelling choice concerns the degree of contractual completeness. The recent contracting literature has debated this with a lot of verve. In subsections 4.1 we examine the incomplete, and in subsection 4.2. the complete contracting model. In subsection 4.3., we explore more deeply the differences in the underlying assumptions, and discuss their reasonableness in the specific context of scientists contracting with their TTO.

The time line of the model with incomplete contracts is as follows. The scientist discloses a scientific discovery to the TTO (we revisit this in section 5.2). A patent is filed at this point (provided there is patent protection). The TTO then searches for a firm with complementary assets. Once a match is found, the firm, the TTO, and the scientist bargain over access to the intellectual property, as well as a consulting agreement. The timeline of the complete contract model is the same, except that the scientist and TTO can write a contract at the beginning of the search stage. Since the complete contracts model builds on the incomplete contracts model, we begin with the latter.

4.1 Incomplete contracts

To solve the model, we first solve the bargaining game at the beginning of the development stage. This is a three-person bargaining game between the firm, the scientist, and the TTO. To apply the Shapley value, we need to examine all possible subcoalitions.

[10] This assumption may be more extreme than reality, in the sense that technology transfer offices pay at least lip service to the notion that they balance the interests of the university, the scientists, and possible even industry. Using the more extreme assumption has the benefit of clarity. Relaxing it might also entail some technical difficulties, since it requires defining a utility function over other player's utility functions, and then using this to solve a bargaining game.

Another interesting point to note is that, in the complete contracts case, the TTO behaves selfishly, but the optimal contract endogenously induces it to internalize the scientist's benefits.

Consider first the case with patent protection. The value of the grand coalition, denoted by v_{FST}, is the expected return from development, i.e., $v_{FST} = \pi$. The value of the sub-coalition involving the firm and the scientist is $v_{FS} = 0$, since they cannot develop the discovery without access to the intellectual property. The value of the sub-coalition involving the firm and the TTO is given by $v_{FT} = \pi_0$, which is the expected return when development occurs without the scientist's involvement. The value of the sub-coalition involving the scientist and the TTO is given by $v_{ST} = U_S^P + U_T^P$, where from (2), the respective ex-ante utilities are given by $U_S^P = \dfrac{m_T^P u_S^P}{r+\delta+m_T^P}$ and $U_T^P = \dfrac{m_T^P u_T^P - c_T^P}{r+\delta+m_T^P}$. The idea is that if the firm is excluded, the scientist and the TTO simply have to start afresh and find a new partner. The value of the firm alone is $v_F = 0$ and the value of the scientist alone is $v_S = 0$, since neither party has the intellectual property. Interestingly, the TTO alone can generate some value, since it can try to find a new firm, and then license out the technology without the scientist's cooperation. We use the subscript $T\backslash S$ to denote all outcomes that are associated with the TTO acting alone, and write $v_T = U_{T\backslash S}^P$.[11]

In general, the Shapley value is given by

$$\begin{aligned} u_F &= \frac{1}{3}(v_{STF} - v_{ST}) + \frac{1}{6}(v_{SF} - v_S) + \frac{1}{6}(v_{TF} - v_T) + \frac{1}{3}v_F \\ u_S &= \frac{1}{3}(v_{STF} - v_{TF}) + \frac{1}{6}(v_{SF} - v_F) + \frac{1}{6}(v_{ST} - v_T) + \frac{1}{3}v_S \\ u_T &= \frac{1}{3}(v_{STF} - v_{SF}) + \frac{1}{6}(v_{TF} - v_F) + \frac{1}{6}(v_{ST} - v_S) + \frac{1}{3}v_T \end{aligned}$$

Applying this to the model with patents, we obtain

$$\begin{aligned} u_F^P &= \frac{1}{3}\pi - \frac{1}{3}(U_S^P + U_T^P) + \frac{1}{6}\pi_0 - \frac{1}{6}U_{T\backslash S}^P \\ u_S^P &= \frac{1}{3}\pi - \frac{1}{3}\pi_0 + \frac{1}{6}(U_S^P + U_T^P) - \frac{1}{6}U_{T\backslash S}^P \\ u_T^P &= \frac{1}{3}\pi + \frac{1}{6}\pi_0 + \frac{1}{6}(U_S^P + U_T^P) + \frac{1}{3}U_{T\backslash S}^P \end{aligned} \tag{10}$$

This describes the utilities for the development stage.[12]

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[11]To calculate the value of $U_{T\backslash S}^P$, from (2), we have $U_{T\backslash S}^P = \dfrac{m_{T\backslash S}^P u_{T\backslash S}^P - c_{T\backslash S}^P}{r+\delta+m_{T\backslash S}^P}$, and, from (6), we have $u_{T\backslash S}^P = \dfrac{\pi_0(r+\delta+m_{T\backslash S}^P) - c_{T\backslash S}^P}{2(r+\delta)+m_{T\backslash S}^P}$. Moreover, $e_{T\backslash S}$ replaces e_S in (7). Note also that in the two-sided model, e_F remains unaffected, since $e_{T\backslash S}$ concerns an off-the-equilibrium path event.

[12]Note that $(U_S^P + U_T^P)$ depends on u_S^P and u_T^P. It is tedious but straightforward to simultaneously solve the second and third equation, to obtain $U_S^P + U_T^P = \dfrac{(4\pi - \pi_0 + U_{T\backslash S}^P)m_T^P - 2\dfrac{3r+3\delta+4m_T^P}{3r+3\delta+3m_T^P}c_T^P}{6r+6\delta+4m_T^P}$. Replacing this in (10) provides a direct expression of the solutions for u_F^P, u_S^P and u_T^P.

To complete the model, we note that the equilibrium is again described by equations (4), (7) and (8) except that we use e_T and c_T, instead of e_S and c_S.

We can contrast this equilibrium with the equilibrium that obtains in the regime without patents. Patenting affects the value of sub-coalitions, and has therefore an important effect on relative bargaining power. The value of the grand coalition remains the same, i.e., $v_{FST} = \pi$. The value of the sub-coalition involving the firm and the scientist is now also given by $v_{FS} = \pi$, since without patent rights, the TTO cannot prevent development to occur. The value of the sub-coalition involving the firm and the TTO is again given by $v_{FT} = \pi_0$. The value of the sub-coalition involving the scientist and the TTO is now given by $v_{ST} = 0$, since the firm can always develop the discovery on its own. Indeed, that is why we also have $v_F = \pi_0$ and $v_S = v_T = 0$. Using these coalition values, we obtain the following Shapley values for the model without patents

$$u_F^N = \frac{\pi + \pi_0}{2},\ u_S^N = \frac{\pi - \pi_0}{2} \text{ and } u_T^N = 0. \tag{11}$$

We immediately note that the firm and the scientist obtain the same bargaining shares as in (5), which pertains to the model without any TTO. The reason for this is simple but profound: without patents, the TTO creates no additional value, after a match has been made. This means that it wields no bargaining power, and hence obtains no returns. Naturally, this affects its incentives at the search stage. From (7) we immediately note that the optimal choice is simply $e_T = 0$: without the prospects of any rewards, the TTO is unwilling to invest in search.

Consider now whether the scientist wants to delegate. Since $c'_S > c'_T$, delegation is always efficient. Moreover, with patent protection we have $u_T^P - u_S^P = \frac{1}{2}(\pi_0 + U_{T\backslash S}^P) > 0$, indicating that the TTO always has more bargaining power than the scientist. With a lower marginal cost, and a greater share of the joint marginal benefits, it is immediate that the scientist always wants to delegate search to the TTO. Contrast this with the no patenting regime. The scientist never wants to delegate to the TTO, since it does not provide any search effort at all. We have thus shown the following important result:

Proposition 3 *With incomplete contracts, the effect of patenting is to enable delegation of search activities to the TTO.*

4.2 Complete contracts

The previous section assumed a contractual incompleteness, where at the beginning of the search stage the scientist and the TTO do not write any contracts that govern the search process. We now examine the case of complete contracts, where the scientist and the TTO can write a contract that can specify rewards for successfully identifying a development partner. Contract completion relates only to the scientist and the TTO. There always remains the more fundamental incompleteness, namely that these two parties cannot write contracts with potential partner firms at the search stage, simply because at that stage they don't know who the relevant partner is.

We now assume that it is possible to write a contract that specifies a transfer τ from the scientist to the TTO, in case of a successful match. In addition, let ς denote any ex-ante transfer from the scientist to the TTO. For simplicity we assume no wealth constraints, nor any other contractual limitations, so that τ and ς can take any positive or negative value. We denote the utilities in the complete contracts model with a tilde, so that $\widetilde{u}_S = u_S - \tau$, $\widetilde{u}_T = u_T + \tau$. Moreover, $\widetilde{U}_S = U_S(\tau) - \varsigma$ and $\widetilde{U}_T = U_T(\tau) - \varsigma$, where $U_S(\tau) = \dfrac{m_T \widetilde{u}_S}{r + \delta + m_T}$ and $U_T(\tau) = \dfrac{m_T \widetilde{u}_T - c_T}{r + \delta + m_T}$.

Proposition 4 *With complete contracts, delegating search to the TTO is always optimal, with or without patenting. The optimal contract always allocates all the benefits from finding a match to the TTO (i.e., $\tau^* = u_S > 0$), and compensates the scientist through an ex-ante transfer (i.e., $\varsigma^* < 0$).*

The proof is in the appendix. Proposition 4 establishes that, irrespective of the patenting regime, a complete contract allows the scientist to always delegate search activities to the TTO. The optimal contract allocates all the returns from search to the TTO, which allows the TTO to internalize the joint benefits of search. The optimal contract also specifies that the TTO makes an ex-ante transfer payment to the scientist. In essence, the optimal contract specifies that, in return for a fixed payment, the scientist transfer all her intellectual property rights to the TTO, which becomes the residual claimant. Transferring the intellectual property to the TTO is efficient, since it provides optimal incentives. The optimal contract gives the scientist a utility $\widetilde{u}_S = 0$. This means that the scientist does not get any of the surplus at the development stage. However, she still receives compensation to cover her development costs d_S.

Mathematically, incomplete contracts are a special parameter case of the model with complete contracts, where $\tau = \varsigma = 0$. Since this parameter constellation is never optimal, we deduce that contract completion always increases the scientist's and TTO's utilities. Complete contracts allow the TTO to internalize the scientist's concerns.

4.3 Discussion

In this subsection we discuss how reasonable complete contracts are in the specific context of our model. The most critical assumptions is that it is possible to make a transfer τ, that is contingent on finding a true match. Consider first the case where there are patents. The verifiable event that triggers the transfer τ is the licensing (or sale) of the intellectual property rights to a firm that wants to further develop the scientific discovery. It seems reasonable to suppose that the scientist and the TTO can specify such a contingency in their initial agreement, given that licensing of a specific technology is a tightly defined event.

We contrast this with the case where there are no patents. In this case, there won't be any licensing contract. The only thing that is likely to occur is a consulting agreement between the scientist and the firm. Turning a consulting contract into the verifiable event that triggers the transfer payment τ is much more problematic. Unlike with licensing, it is much harder to ascertain whether a consulting agreement pertains to a specific discovery. Once the TTO has found a match, the scientist has an incentive to engage in a consulting agreement with the firm, but claim that this consulting agreement is unrelated to the original discovery. This avoids paying the transfer payment τ. In fact, it may even be possible for the scientist not to disclose to the university that any consulting agreement has been signed, or to structure the consulting agreement through a third party, such that it can no longer be traced to the specific firm.[13]

The interesting point is that the assumption of whether the scientist and the TTO can reasonably write an ex-ante contract depends itself on the patenting regime. A benefit of having patents is that it facilitates the writing of contracts, because the licensing of a patent provides a verifiable event itself. This suggests the conclusion that if patents exist, delegation to the TTO is always possible. The patent facilitates the writing of a complete contact, which allows the TTO to internalize the joint benefits of search. In this case, the model with the TTO essentially mirrors the model of section 3, with search being performed by the TTO. However, if no patents exists, then the scientist and the TTO might find it is difficult to write complete contracts. This may lead to a break-down of delegation. In this case, the model with the TTO also mirrors the model of section 3, with search being performed by the scientist herself.

The discussion so far focusses on the difficulties of on the contingent transfer τ. There may be another set of problems with the unconditional transfer payment ς. The optimal contract requires that the TTO pays the scientist for her discovery. This can lead to a severe adverse selection problem, where every scientist in the university suddenly "claims" to have a discovery, that deserves to be compensated by the TTO. To prevent adverse selection, the TTO compensates only those discoveries that prove to have development potential. That means no ex-ante transfers to the scientist, i.e., $\varsigma \geq 0$.[14]

[13] Purists may object that if intellectual property is verifiable to a patent office (or a patent court), then it should also be verifiable in private contracts (or a standard court). However, patenting has a much more standardized process, suggesting lower costs of contracting. And patenting has well-defined rules and regulations, as well as a substantial amount of precedence, which creates better enforceability.

[14] It is straightforward to model this formally. Assume that there are two types of discoveries that the TTO cannot distinguish ex-ante. One is truthful, as described in the main model. The other one is fake, never generates any value, and never attracts any partner firm. Suppose that the number of potential fake discoveries is large. To induce self-selection, the TTO only needs to charge any $\varsigma > 0$

If adverse selection prevents unconditional transfer payments to scientists, we have a constrained contracting model. We briefly outline the main insights from such a model. If it is impossible to contract on τ (as discussed above), then there is no point for any ex-ante contract, and the model reverts to the incomplete contract model. If contracting on τ is possible, it is easy to see that the optimal ς satisfies $\varsigma = 0$ (or equivalently $\varsigma \to 0$). This is because the scientist has no need or desire to compensate the TTO. What the scientist may want to do, however, is to provide further incentives to the TTO. This means setting $\tau > 0$. The alternative is to set $\tau = 0$, which effectively means reverting to an incomplete contract. In the appendix we derive the formal condition for when the scientist sets $\tau > 0$. We show that even if the scientist provides positive incentives, these incentives always fall short of the first-best incentives τ^*. Thus, the constraint $\varsigma \geq 0$ always interferes with the optimal contract from Proposition 4. For the case where the scientist provides no incentives, the optimal contract is no contract at all.

5 Model extensions

5.1 Endogenizing the number of firms and discoveries

So far we assumed that the number of firms (n_F), and the number of new discoveries (s) is exogenous (although the number of scientist that remain in the market (n_S) is endogenous). We now discuss how the model can be extended to allow both of these to be determined endogenously.

To endogenize the number of firms, suppose an investment is required to develop some complementary assets, that allow the firm to become a potential partner, i.e., to become a member of the relevant set of firms n_F. Specifically, suppose that firms have to incur some fixed cost $k \in [0, \infty)$, and that the distribution of fixed costs is characterized by $K(k)$. The entry condition is then simply given by $U_F \geq k$. The endogenously determined number of firms is then given by $n_F = K(U_F)$.

The supply of patentable discoveries may also be endogenous. The literature has identified two main reasons why the return to patents may affect incentives for basic research. One hypothesis is that patents induce greater work effort. This corresponds to the traditional ex-ante argument for patenting. As discussed in the introduction, it is not clear that provision of effort is a major concern for scientists. A second, and potentially more important incentive effect related to a multi-tasking choice between basic research, which is assumed to be unpatentable, and applied research, which may potentially lead to a patent. For simplicity suppose that each scientist chooses one or the other career path, and assume that relative aptitudes and preferences for doing basic versus applied research can be described by the following simply utility function: $\Upsilon_S = Max[a(U_S), b]$, where $a(U_S)$ is the return to applied research, and b

(including $\varsigma \to 0$).

the expected utility of doing basic research. Suppose that b has a distribution $B(b)$ over $[0, \infty)$. A scientist pursues an applied research agenda whenever $b \leq a(U_S)$. Let $s(B)$ denote the number of new applied discoveries that are generated if B scientists are dedicated to applied research. Since $s(B)$, $B(a)$ and $a(U_S)$ are all increasing functions, the supply of new discoveries s is an increasing function of U_S. We write $s(U_S)$, which is a short-hand for $s(B(a(U_S)))$.

Consider now the model where both the number of firms and discoveries is endogenous. We augment the equilibrium conditions with the additional equations $n_F = K(U_F)$ and $s = s(U_S)$. We have already seen that the effect of patenting is to increase u_S , but to decrease u_F. In general, patenting also increases U_S and decreases U_T.[15] Patenting has some additional effects if the number of firms and scientists is endogenous. A higher value of U_S increases the supply of applied researchers, increasing the arrival rate of new discoveries. Similarly, a lower value of U_F decreases the supply of firms that are willing to invest in complementary assets. In addition to affecting the (ex-post) search intensities, patenting thus affects the (ex-ante) investment decisions. The effects are in line with the standard results from the ex-ante literature.

5.2 Voluntary disclosure

So far, in the model with the TTO, we assumed that the scientist is willing to disclose her discovery to the university. Without patent protection, disclosure is irrelevant, but otherwise disclosure is the first step towards a patent application. Instead of disclosing her discovery, the scientist can search by herself for a partner firm. The major drawback is that this way she cannot file a patent, since the university could lay a claim on the patent. The best the scientist can expect without disclosure is thus to get a consulting contract.

To analyze the disclosure decision, consider first the case of incomplete contracts. With disclosure the scientist's utility is given by $U_S^P = \dfrac{m_T u_S^P}{r + \delta + m_T}$ where $u_S^P = \dfrac{1}{3}\pi - \dfrac{1}{3}\pi_0 + \dfrac{1}{6}(U_S^P + U_T^P) - \dfrac{1}{6}U_{T\backslash S}^P$. Without disclosure the scientist obtains $U_{S\backslash T}^N = \dfrac{m_{S\backslash T} u_{S\backslash T}^N - c_{S\backslash T}}{r + \delta + m_{S\backslash T}}$ where $u_{S\backslash T}^N = \dfrac{\pi - \pi_0}{2}$. The scientist benefits from disclosure whenever $\dfrac{m_T u_S^P}{r + \delta + m_T} > \dfrac{m_{S\backslash T} u_{S\backslash T}^N - c_{S\backslash T}}{r + \delta + m_{S\backslash T}}$. This condition is easily satisfied, such as when the scientist has large search costs $c_{S\backslash T}$. The more interesting issue is whether the condition can be violated, so that the scientist refused to disclose her discovery. To show that this is indeed possible, we focus on the case where tacit knowledge is important. Specifically, we consider the case where $\pi_0 \to 0$. This implies

[15] Section 3 discuses some exceptions to this. The analysis of these case is straightforward, and need not concern us here.

$U^P_{T\backslash S} \to 0$, so that $u^P_S - u^N_{S\backslash T} = \frac{1}{6}(U^P_S + U^P_T - \pi) < 0$ (since $\pi > u^P_S + u^P_T > U^P_S + U^P_T$). This says that for the scientist, disclosure has a disadvantage in terms of a lower return from finding a match. Naturally, one advantage of disclosure is that it saves the scientist the cost of search ($c_{S\backslash T}$). Finally, we want to know whether delegation to the TTO results in a higher probability of finding a match. The values m_T and $m_{S\backslash T}$ depend both on marginal benefits and costs. On the benefits side, we note that for $\pi_0 \to 0$, we have $u^P_T \to u^P_S < u^N_{S\backslash T}$. This says that the TTO has a lower benefit than the scientist. If the TTO has a sufficiently large cost advantage over the scientist, we may still obtain $m_T > m_{S\backslash T}$. But for a sufficiently small cost advantages, we obtain $m_T < m_{S\backslash T}$. Suppose now that the scientist's search costs are sufficiently small, and sufficiently close to the TTO's costs. In this case the advantages of disclosure are small, but the disadvantage of disclosure remain large. We have thus constructed an example where the scientist prefers not to disclose her discovery, in order to avoid having to share returns with the TTO. Non-disclosure obviously negates any benefits of patenting, since the equilibrium reverts to the no patenting outcome.

In the model with complete contracts, disclosure becomes relatively more attractive to the scientist. This simply follows from the fact that at the initial bargaining stage with the TTO, the scientist has, as her outside option, the utility of the incomplete contracts model. In the negotiation she receives a utility higher than this outside option. Hence disclosure becomes relatively more attractive.

So far we assumed that the scientist remains with the university. An additional complication arises if the scientist can leave the university and pretend that the discovery was made after leaving. The feasibility of this obviously depends on the nature of the discovery, but the option of leaving can become an attractive alternative to disclosure. This typically applies less to tenure-line faculty, but is particularly important for graduate students. A curious and unintended consequence of patenting might be the departure of talented researchers from university.

5.3 Imperfect patent protection

So far we assume that either there is no patent protection, or patent protection is perfect. We now consider the case of imperfect patent protection. For this, we use a simple model of imperfect enforceability. We allow for efficient pre-trial bargaining, and we assume common priors. To model the uncertainty in the court system, let q be the probability that a court upholds the patent. It is convenient to express the expected legal costs as a fraction of the value at stake x, i.e., suppose legal costs are given by $\psi_F x$ and $\psi_S x$, where $\psi_F, \psi_S \in (0, \infty)$. If the patent is upheld, we assume that the offender has to pay the patentee a licensing fee of λx, where $\lambda \in (0, \infty)$. If the court revokes the patent, the alleged offender can proceed freely. Prior to going to court, the two parties can settle. The expected utilities of going to court are given by $q\lambda x - \psi_S x$ and $x - q\lambda x - \psi_F x$. Note that for $q < \frac{\psi_S}{\lambda}$, the threat of going to court is never credible, since the cost outweigh the expected benefits. In this case the firm can simply ignore the patent, which is de facto not enforceable. For $q > \frac{1-\psi_F}{\lambda}$, the firm prefers not to infringe, rather than be dragged into court. In this case, the firm always agrees to obtain a license up-front. The patent is de facto perfectly enforceable.

Consider now the intermediate case where $\frac{\psi_S}{\lambda} < q < \frac{1-\psi_F}{\lambda}$. In this case, the two parties would prefer to settle out of court. The gains from a pretrial settlement are the legal cost savings $(\psi_F+\psi_S)x$. The Nash bargaining solution yields $q\lambda x-\psi_S x+\frac{1}{2}(\psi_F+\psi_S)x = (q\lambda+\frac{\psi_F-\psi_S}{2})x$ and $x-q\lambda x-\psi_F x+\frac{1}{2}(\psi_F+\psi_S)x = (1-q\lambda-\frac{\psi_F-\psi_S}{2})x$.

At the beginning of development stage, the two parties can sign a licensing agreement. Strictly speaking, the firm is indifferent between striking a licensing agreement, or waiting for a pre-trial bargaining. We focus on the more intuitive scenario, where the firm agrees to take a license up-front, but pays a reduced fee that reflects imperfect enforceability. The transfer α satisfies $u_S = \alpha = px(q\lambda + \frac{\psi_F-\psi_S}{2}) - d_F$, which is an increasing function of q. By varying q, the model with imperfect enforceability spans the spectrum from no to perfect patent protection. Put differently, for every $\alpha \in [0, u_S^P]$, we can find a corresponding q that generates that value of α. The model with imperfect patent protection convexifies the discrete distinction between the no patent and the perfect patent regime.

The analysis of imperfect patents has another interesting implication. From the analysis in section 3, it is easy to see that the value of $e = e_F + e_S$ is a concave function of α. For sufficiently high values of c_F' (and/or sufficiently low values of c_S'), e is increasing throughout the range $\alpha \in [0, u_S^P]$, and for sufficiently low values of c_F' (and/or sufficiently high values of c_S'), e is decreasing throughout the range $\alpha \in [0, u_S^P]$. But for intermediate values of c_F' and c_S', e has an interior maximum in $\alpha \in [0, u_S^P]$. At low levels of patent protection (implying a low value of α), increasing patent protection increases licensing rates. However, at high levels of patent protection (implying a high value of α), increasing patent protection may decrease licensing rates. Lerner (2002) provides related evidence that suggests a similar inverse-U relationship between patent protection and patenting rates.

5.4 Complementary search process

So far we assumed that the matching process consists of independent searches. We briefly consider an alternative model where it is impossible to find a firm, unless it makes an effort to be found - and similarly for a scientist. One can think of a variety of model specification here, but we focus on a simple of model "double coincidence:" For a match to occur, both parties have to make an effort. A simple example would be if firms and scientist have to rely on meeting each other in a common location (such as a conference). The instantaneous probability of a match is now given by $e = e_S * e_F$. Straightforward calculations show that the steady state first order conditions are given by

$$n_F e_F (u_S - U_S) - c'_S = 0 \text{ and } n_S e_S u_F - c'_F = 0.$$

Using similar reasoning as before, this can be rewritten as

$$n_F e_F \frac{(r+\delta)u_S + c_S}{r + \delta + n_F e_S e_F} - c'_S = 0 \text{ and } e_S \frac{s u_F}{\delta + n_F e_F e_S} - c'_F = 0.$$

One interesting result is that the steady state reaction functions are no longer substitutes, but complements.[16]

With this, we immediately recognize the most interesting aspect of the meeting model: there may be multiple equilibria.[17] Indeed, there always exists an equilibrium where $e_S = e_F = 0$. That is, there always exists an equilibrium where the market collapses, because each side of the market is waiting for the other to make itself visible. Scientists do not invest in search, because firms are impossible to find, and vice versa. In addition to such this coordination failure equilibrium, there may exist one or several equilibria where both parties do invest in search (i.e., $e_S, e_F > 0$).

6 Conclusion

In this paper we examine an ex-post rationale for the patenting of scientific discoveries. At the core of the model is the problem that scientists rarely know what industrial applications may exist for their scientific discoveries. At the same time firms are often unaware what scientific discoveries might help them with their needs. We call this the science to market gap. The gap can be bridged when scientists and firms engage in a process of search and communication. Since patenting affects the distribution of rents, it can have a profound effect on the relative search intensities of firms and scientists. Patenting scientific discoveries bolsters the scientific community to "push" their discoveries out to industry. However, it may also dampen firms' incentives to "pull" discoveries out of academia. The net effect of patenting depends on the relative ease of bridging the science to market gap through "push" or "pull."

[16] To see this, simply note that the scientists' marginal benefit can be rewritten as $n_F \frac{(r+\delta)u_S + c_S}{\frac{r+\delta}{e_F} + n_F e_S}$, which is increasing in e_F. Similarly, the firms' marginal benefit can be rewritten as $\frac{s u_F}{\frac{\delta}{e_S} + n_F e_F}$, which is increasing in e_S.

[17] Milgrom and Shannon (1994) provide a very general theorem of how complementarities in reaction functions can generate multiple equilibria.

The model also examines the importance of universities' technology transfer offices. In principle such offices allow for task specialization. Scientist benefit from delegating search activities to them, which may free them up to pursue further research. However, the model explains that such delegation typically requires patenting. This argument generates a separate rationale for the patenting of scientific discoveries.

As with any economic theory, our model has some restrictive assumptions, and reality is always more complex. This leaves the door open for a lot of future research. Our paper does not look at issues of market structure. This is partly because there already exists a large literature of the competitive implications of patenting and licensing. Still, it would be interesting to see how integrating this affects the current framework. Our analysis is also focussed on the use of a scientific discovery for developing a new industrial application. It ignores the use of a scientific discovery for further scientific work. Murray and Stern (2005) provide evidence that patenting of scientific discoveries may have a negative impact on further scientific progress. Future research could examine the desirability of patenting when scientific discoveries have multiple uses, some industrial and others scientific.

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8 Appendix

Proof of Proposition 1:

Let $\theta_S = u_S - U_S$. The second order condition requires $-n_F \frac{d\theta_S}{de_S} - c''_S < 0$. Using (2) we get $\theta_S = u_S - \frac{n_F e_S u_S - c_S}{r+\delta+n_F e_S}$. It is useful to also rewrite this as $\theta_S = \frac{(r+\delta)u_S + c_S}{r+\delta+n_F e_S}$, so that $\frac{d\theta_S}{de_S} = \frac{(r+\delta+n_F e_S)c'_S - ((r+\delta)u_S + c_S)n_F}{(r+\delta+n_F e_S)^2}$. Using the first order condition (7), we note that $\frac{d\theta_S}{de_S} = \frac{n_F[((r+\delta)u_S + c_S) - ((r+\delta)u_S + c_S)]}{(r+\delta+n_F e_S)^2} = 0$. Thus convexity of c_S guarantees that the second order condition is always satisfied.

The effect of patenting is to increase u_S. We have $\frac{d\theta_S}{du_S} = 1 - \frac{n_F e_S}{r+\delta+n_F e_S} = \frac{r+\delta}{r+\delta+n_F e_S} > 0$, so that $\frac{de_S}{du_S} = \frac{-1}{c''_S} n_F \frac{d\theta_S}{du_S} > 0$.

Proof of Proposition 2:

We use $u_S = \alpha$ and $u_F = \pi - \alpha$. We represent stronger intellectual property protection as an increase in α. We totally differentiate the two equations in (9) with respect to α, and obtain $\begin{pmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{pmatrix} \begin{pmatrix} de_S \\ de_F \end{pmatrix} + \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} d\alpha = 0$, where $x_{11} = -c''_S < 0$,[18] $x_{12} = -n_F \frac{n_F(r\alpha + \delta\alpha + c_S)}{(r+\delta+n_F e_F + n_F e_S)^2} < 0$, $x_{21} = -n_F \frac{s(\pi-\alpha)}{(\delta+n_F e_F+n_F e_S)^2} < 0$, $x_{22} = -\frac{n_F s(\pi-\alpha)}{(\delta+n_F e_F+n_F e_S)^2} - c''_F < 0$, $y_1 = \frac{n_F(r+\delta)}{r+\delta+n_F e_F+n_F e_S} > 0$, and $y_2 = -\frac{s}{\delta+n_F e_F+n_F e_S} < 0$. Thus $\begin{pmatrix} de_S \\ de_F \end{pmatrix} = \frac{-1}{x_{11}x_{22} - x_{12}x_{21}} \begin{pmatrix} x_{22} & -x_{12} \\ -x_{21} & x_{11} \end{pmatrix} \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} d\alpha$. The condition $\frac{-1}{x_{11}x_{22} - x_{12}x_{21}} < 0$ ensures that the equilibrium is stable. Thus $\frac{de_S}{d\alpha} = -\frac{x_{22}y_1 - x_{12}y_2}{x_{11}x_{22} - x_{12}x_{21}} > 0$ and $\frac{de_F}{d\alpha} = -\frac{x_{11}y_2 - x_{21}y_1}{x_{11}x_{22} - x_{12}x_{21}} < 0$. In addition, note that $\frac{d(e_S + e_F)}{d\alpha} = \frac{(x_{21} - x_{22})y_1 + (x_{12} - x_{11})y_2}{x_{11}x_{22} - x_{12}x_{21}}$. We note that this is increasing in x_{11}, and thus decreasing in c''_S. Hence, if scientists have sufficiently steep marginal costs, then an increase in intellectual property rights increases e_S by less than it decreases e_F.

Proof of Proposition 4:

The optimal ex-ante contract maximizes $\widetilde{U}_S + \widetilde{U}_T$. For $c'_S > c'_T$, it is always more efficient that the TTO incurs the search costs. Straightforward calculations reveal

[18] To see that x_{11} reduces to $x_{11} = -c''_S$, we totally differentiate the first equation w.r.t. e_S and obtain $\frac{n_F c'_S(r+\delta+n_F e_F+n_F e_S) - n_F(r\alpha+\delta\alpha+c_S)n_F}{(r+\delta+n_F e_F+n_F e_S)^2} - c''_S$. We then use the first condition again, which can be rewritten as $c'_S(r+\delta+n_F e_F+n_F e_S) = n_F(r\alpha+\delta\alpha+c_S)$. Thus $x_{11} = -c''_S$.

that the jointly optimal search effort is now given by the following variant of equation (7): $n_F(u_S + u_T - U_S(\tau) - U_T(\tau)) - c_T' = 0$. Naturally, the TTO continues to optimize privately, so that e_T satisfies $n_F(\widetilde{u}_T - U_T(\tau)) - c_T' = 0$.[19] The optimal τ needs to satisfy $\widetilde{u}_T - U_T(\tau) = u_S + u_T - U_S(\tau) - U_T(\tau) \Leftrightarrow \tau = u_S - U_S(\tau)$. This is always satisfied for $\tau^* = u_S$, since $\tau^* = u_S \Leftrightarrow \widetilde{u}_S = 0 \Leftrightarrow U_S(\tau^*) = 0$.

To see that $\varsigma < 0$, we simply consider the ex-ante Nash bargaining game between the scientist and the TTO. In case of disagreement, we assume that the two parties simply proceed without a contract. In this case, the model reverts back to the incomplete contracts setting. Thus, $\widetilde{U}_S = \dfrac{U_S(\tau^*) + U_T(\tau^*) + U_S - U_T}{2}$ and $\widetilde{U}_T = \dfrac{U_S(\tau^*) + U_T(\tau^*) - U_S + U_T}{2}$. Using $\widetilde{U}_S = U_S(\tau^*) - \varsigma$ and $U_S(\tau^*) = 0$, we obtain $\varsigma^* = -\dfrac{U_T(\tau^*) - U_T + U_S}{2} < 0$.

Analysis of the model with $\varsigma \geq 0$

We briefly sketch the model where the scientist can provide incentives to the TTO. The scientist maximizes $U_S(\tau) = \dfrac{m_T(u_S - \tau)}{r + \delta + m_T}$, subject to the first-order condition of $e_T(t)$, given by $n_F[u_T(t) + \tau - \dfrac{1 - \delta\Delta}{1 + r\Delta} U_T(\tau, t + \Delta)] - c_T'(t) = 0$. We note that $\dfrac{dU_S(\tau)}{d\tau} = \dfrac{(u_S - \tau)(r + \delta)}{(r + \delta + m_T)^2} \dfrac{dm_T}{d\tau} - \dfrac{m_T}{r + \delta + m_T}$, where the first term captures the benefit of increasing incentives, and the second term captures the cost of providing incentives. To evaluate the incentive effect we use $U_T(\tau) = \dfrac{m_T(u_T + \tau) - c_T}{r + \delta + m_T}$ and totally differentiate the first order condition. For $\Delta \to 0$ we have $n_F[1 - \dfrac{m_T}{r + \delta + m_T}]d\tau - c_T'' de_T(t) = 0 \Leftrightarrow \dfrac{de_T}{d\tau} = \dfrac{n_F}{c_T''} \dfrac{(r + \delta)}{r + \delta + m_T}$. Using $\dfrac{dm_T}{d\tau} = n_F \dfrac{de_T}{d\tau}$ we finally obtain $\dfrac{dU_S}{d\tau} = \dfrac{(n_F)^2 (r + \delta)^2}{(r + \delta + m_T)^3} \dfrac{(u_S - \tau)}{c_T''} - \dfrac{m_T}{r + \delta + m_T}$. The constrained optimal τ is positive whenever $\dfrac{dU_S}{d\tau} > 0$ at $\tau = 0$. We obtain three results. First, higher values of u_S increase $\dfrac{dU_S}{d\tau}$, meaning that the scientist has a stronger desire to voluntarily provide incentives. Second, higher values of c_T'' decrease $\dfrac{dU_S}{d\tau}$, showing that the scientist is less interested in providing incentives when the TTO's search behavior is inelastic. Third, even if the scientist provides incentives, the constrained optimal τ always lies below the unconstrained optimal $\tau^* = u_S$. At τ^*, the first term is zero, indicating that the marginal benefit of providing benefit is zero, while the marginal cost remains positive.

[19] Note that the ex-ante transfer ς does not influence this equation, hence the use of $U_T(\tau)$, rather than $\widetilde{U}_T(\tau)$.