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Patents vs trade secrets : knowledge licensing and spillover

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Abstract

We develop a model of two-stage cumulative research and development (R&D), in which one Research Unit (RU) with an innovative idea bargains to license her nonverifiable interim knowledge exclusively to one of two competing Development Units (DUs) via one of two alternative modes: an Open sale after patenting this knowledge, or a Closed sale in which precluding further disclosure to a competing DU requires the RU to hold a stake in the licensed DU's post-invention revenues. Both modes lead to partial leakage of RU's knowledge from its description, to the licensed DU alone in a closed sale, and to both DUs in an open sale. We find that higher levels of interim knowledge are more likely to be licensed via closed sales. If the extent of leakage is lower, more RUs choose open sales, generating a non-monotonic relationship between the strength of Intellectual Property Rights (IPR) and aggregate R&D expenditures and the overall likelihood of development by either DU.

JEL Codes: D23, O32, O34.

1 Introduction

We develop a model of two-stage cumulative research and development (R&D), in which a Research Unit (RU, e.g., a biotech company) invests in research to produce an interim innovative idea ("Knowledge"). The idea has no value to consumers but it could be developed further into a marketable product by one of two competing Development Units (DUs, e.g., large pharmaceutical companies). The latter are assumed to be far more efficient in developing the idea than the original research unit itself, by virtue of having deep pockets, which would allow it to avoid the incentive losses arising from external financing of development costs,[1] and via owning specific complementary assets or skills. We study the trade-offs between different mechanisms for selling or licensing such ideas, involving patenting of the knowledge or relying on trade secrets. We then characterize when each of these licensing mechanisms is more likely to be chosen, and derive the implications of these choices for the structure of licensing fees. In particular, we focus on the choice over (combinations of) lump-sum vs. revenue-contingent royalties, taking into account their impact on development incentives, and the viability of exclusive licensing.

Our analysis, which extends the important work of Anton and Yao (1994, 2004), takes into account the possibility of partial knowledge spillover to non-licensees arising from the description of knowledge provided in the process of patenting, only part of which can be adequately codified to preclude non-utilization of key ideas contained by others. The extent to which innovative ideas can be protected via patenting differs a great deal across industries and products and can be viewed as the strength of intellectual property rights, or IPR. A related notion, emphasized in Anton and Yao (1994), is the degree to which mere description of an innovative idea, to a potential licensor for its development, enables its recipient to use it opportunistically without further elaboration by or payment to its originator. Both these leakage or spillover parameters, as well as the quality of the interim knowledge itself, as measured by the maximum likelihood of final invention that it gives rise to, are shown to affect the privately optimal choice of the mode of licensing. In addition, we also explore how these leakage effects, as well as the ex ante distribution of interim innovative knowledge levels, affects the overall level of development efforts and thereby the the overall probability of successful development of the idea.

These issues are certainly important in a modern economy. As Scotchmer (1991) notes, "Most innovators stand on the shoulders of giants, and never more so than in the current evolution of high technologies, where almost all technical progress builds on a foundation provided by earlier innovators." In 2003, in-licensed products accounted for more than $70 billion in revenues for the top 20 pharmaceutical companies (Wood Mackenzie, 2004); on average, this corresponds to a quarter of their total revenue now and is expected to increase to 40 per cent in a few years. The leading pharmaceutical companies have large R&D budgets (about 15-20% of sales revenues), and yet rely increasingly on outside research. Since its creation in 2000, GlaxoSmithKline (GSK) has radically restructured its approach to R&D and moved from 2-3 in-licensing deals a year to more than 10 every year (Morais, 2003). The restructuring paid off and other companies followed GSK, competing for both late- and early-stage licensing deals (Featherstone and Renfrey, 2004).

In other industries, such sequential innovation is also important, even though the licensing arrangements vary greatly; outside of a small set of industries (including biotechs) the sellers of knowledge rely on secrecy rather on patents (Cohen et al., 2000). Also, inventors are paid in cash, in stock, through participation in joint ventures, or in revenue-contingent royalties. For example, while purchasing software technology for its Internet Explorer web browser from Spyglass, Microsoft agreed to pay Spyglass about $1 per each copy of Internet Explorer distributed (Bank, 1997). Even without wide use of patents, software firms manage to generate substantial revenue from licensing; the market for intellectual property licensing by software firms is estimated at $100 billion a year (Srikanth, 2003). Both large and small firms are involved in such licensing; yet, as it requires substantial investment before the returns are realized, smaller firms often need a strategy to relax their financial constraints. Licensing their intermediate innovations to larger firms with deeper pockets for development serves such a purpose.

Several issues concerning the licensing of such intellectual property are of substantial interest. Why do both in-house and in-licensed research co-exist? Why are some sales of ideas based on patents and others on trade secrets? What are the roles of lump-sum fees versus contingent royalty payments in providing incentives for research and development? What are the implications of Development Units financing Research Units in exchange for a range of control over their subsequent actions, e.g., right of first offer on licensing ideas?

We attempt to answer some of these questions within an incomplete contract setup where two potential buyers of non-verifiable knowledge compete to obtain a license to develop the knowledge (Figure 1). Unlike conventional incomplete contract models, we take into account not only the fact that the value of such knowledge is not verifiable, but also the imperfect excludability and non-rivalrous nature of knowledge. Imperfect excludability implies that after an item of knowledge is described to a potential buyer, he already captures a certain share of its potential value. Indeed, at least partial imitation of the idea is a credible threat which may weaken the seller's bargaining position. On the other hand, the non-rivalrous nature of knowledge makes it hard for the seller to commit to an *exclusive* sale: after selling knowledge to one buyer, the seller can sell it again to another buyer. If the original buyer of knowledge expects further sales to his competitors, he would pay less than for a solitary license. We explore mechanisms that enable the seller

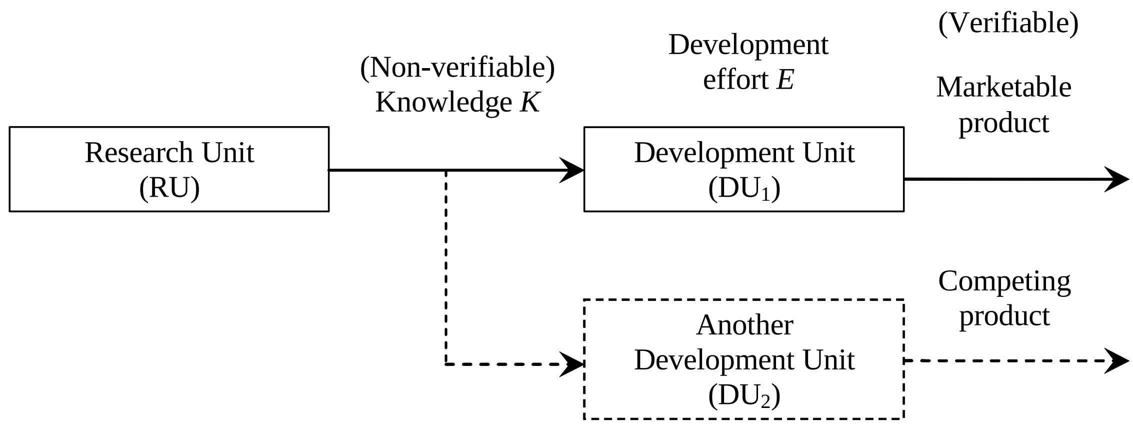

Figure 1: A model of sequential research and development, and knowledge licensing.

to commit to exclusivity.

A conventional approach to assuring exclusive licensing is patenting. Teece (2000, page 22) writes: "Patents are in one sense the strongest form of intellectual property because they grant the ability to exclude, whereas copyrights and trade secrets do not prevent firms that make independent but duplicative discoveries from practicing their innovations and inventions".[2] As Teece (2000) notes elsewhere, the "doctrine of equivalents" (of insubstantial differences), or of a similar "look and feel", are often applied much less stringently in trade secret or trademark litigation than in those over patented innovations. As a result, the licensor of patented interim knowledge finds it much easier to pre-commit to exclusive licensing thereof – which we shall show is privately optimal for her – since if she were to sell her Knowledge to another developer, his final invention would embody the same look-and-feel as the aspects of this knowledge codified in the patent, and will be thus denied a final invention patent. Of course, in reality such enforcement of patents is only probabilistic, as in Anton and Yao (2002), but for simplicity we will assume that patenting is a perfect means for exclusion.

However, patenting also involves a leakage of a certain portion of the knowledge to the public in the process of filing a patent application. This is especially important for most "tacit" (Teece, 2000) or non-codifiable knowledge. Such knowledge is hard to protect using intellectual property rights (IPR) law, since description of the codifiable features of an innovation in a patent nevertheless leaves open many possibilities for inventing around the patent, and creating a final product without the same extent of similar look and feel as one that employed the codifiable aspects of an idea, such as its molecular structure. For example, many innovations in software create possibilities for inventing around, using detailed sub-routines that differ from those in the original invention, but nevertheless utilizing structural notions implicit in the patented idea. Description of an innovation in a patent can then lead to a partial spillover of capabilities for second-stage invention, to parties other than the original innovator, or its licensee for the patented idea. As Cohen, Nelson and Walsh (2000) have noted on the basis of survey data, outside a small set of US industries "patents are considered less effective relative to alternative mechanisms for protecting intellectual assets, such as secrecy and lead times" (Gallini, 2002), because of knowledge spillovers arising from the descriptions involved in the patenting process. As a result, in both US and EU (see Arundel and Kable, 1998 for the latter), only a minority of innovations are patented, typically in industries with highly codifiable innovations.

The alternative arrangement is to sell the knowledge privately, relying on trade secrets. In order to provide the seller with incentives not to resell the knowledge to a competing buyer, the original buyer gives the researcher a share of its future revenues (through an equity stake or through royalties).[3] If this revenue share is sufficiently high, the seller would prefer not to sell the knowledge to the buyer's competitors, because the value of the researcher's royalty stake is contingent on the first buyer acquiring monopoly position in the product market. While others such as Pisano (1989) have suggested a linkage between the co-ownership of equity shares and preventing opportunistic knowledge disclosure, we are the first to fully analyze this mechanism taking into account its effects on both buyers' and sellers' incentives.[4] We also consider alternative private contracts between the buyers and sellers which may support exclusive licensing.[5]

The buyer's incentives to invest in development are undermined if she has to give away a high share of final revenues to the knowledge seller. We explicitly model their extensive form bargaining, and find that the parties are more likely to choose the private (or "closed") mode of licensing over patenting if the interim knowledge is highly valuable and if describing the knowledge involves substantial leakage. The intuition for the latter effect is straightforward. On one hand, greater leakage in the patenting process makes patenting a less attractive option. On the other hand, in closed sales, leakage via private description of knowledge is even helpful as the seller would have a weaker bargaining position in a clandestine opportunistic disclosure to the competitor of the original buyer.

The explanation for more valuable knowledge being licensed privately follows from the detailed comparison of incentives in a revenue-contingent royalty contract, with those arising via patenting before licensing. This comparison takes into account two major effects. The first one is that the share of future revenue that RU has to be given to assure no second sale is decreasing in the level of knowledge. Indeed, the higher the value of the knowledge the more important the value of monopoly invention; therefore lower royalty stake suffices. Hence, RU and her licensee DU capture a higher proportion of the potential value of knowledge as its level increases.

The second effect has to do with the impact of higher levels of knowledge on the non-licensee DUs' effort when patenting knowledge leads to non-trivial enabling spillover of it to him. This effect is not monotonic in knowledge. We analyze the impact of leakage on development efforts as Nash equilibrium outcomes in asymmetric contests for rents arising from final inventions. Higher knowledge for the licensee initially increases not only his but also the non-licensee's invention prospects, which later decrease as levels of licensed knowledge increase further. Thus, the proportion of the potential value of RU's knowledge – which would have accrued to her and her licensee DU without spillovers – captured by her and her licensee in patent-based licensing, is first increasing and then decreasing in RU's knowledge level. Our result arises from these two key effects, plus the possibility of non-existence of share contracts ensuring exclusive closed licensing for low knowledge levels.

The recent paper of Anton and Yao (2004) contains results related to ours on the choice between patenting or otherwise at different levels of know-how, and protection of intellectual property rights. However, these are derived in a context without cumulative R&D, in which the purpose of partial know-how disclosure is to signal one's cost level to product market competitors, and rewards from patenting consist of expected penalties derived from patent infringement suits. These ex post infringement penalties are assumed to be independent of the quality of disclosed knowledge. Anton and Yao (2004) also find that higher-valued innovations (those reducing costs of production the most) would not be patented, but protected as trade secrets with fairly low levels of disclosure. In contrast, Denicolo and Franzoni (2004b), who endogenise the levels of imitation efforts by non-innovators only when the original invention is not patented, find that more valuable inventions with larger markets are more likely to be patented, with others relying on trade secrets.

In our work, we endogenise the licensing fees for interim knowledge via buyer-seller bargaining. We also allow for leakage of knowledge, via its description in private sales or via patenting, to be partial, depending on the nature of the technology as well as possibly patent laws. As a result, the contracting issues arising in our model are richer than in earlier work on knowledge disclosure in cumulative R&D, via patents as in Scotchmer and Green (1990), or via private sales as in the work of Anton and Yao (1994). In these papers such leakage of knowledge was taken to be complete.

We show that the effects above may generate a non-monotonic relationship between the strength of Intellectual Property Rights (IPR) and aggregate R&D expenditures. Some theoretical models pertaining to endogenous quality of innovation, imitation, and ease of second-stage research in a cumulative innovation process have suggested the possibility of a non-monotonic, indeed, "inverted U-shaped" relationship between the strength of IPR protection and R&D activity in a sector or an economy, and a recent empirical study by

Lerner (2001) provides some support for this conjecture.[6] At the same time, as Gallini (2002) notes in a literature survey, "these relationships are difficult to model and test".

In our model, such an inverted U-shaped relationship between the strength of IPR-protection – measured as the complement of the extent of knowledge leakage – does *not* arise if attention is restricted to patented (or "open") sales only. However, once the endogenous choice of licensing mode is taken into account, such a non-monotonic relationship often emerges naturally. Potential leakages of knowledge via its description, prior to its licensing, have quite different effects on the resulting levels of development expenditures in closed versus open modes of licensing, as noted above.[7]Increases in the strength of IPR protection in the patenting process, as well as decreases in the proportion of knowledge leaked in private descriptions thereof, also lead to RUs switching away from closed to open (or patent-based) modes of licensing for higher knowledge levels, which nevertheless results in partial spillover thereof to non-licensees. The overall impact of all these effects, in particular the "mode-switching" effect noted above, can easily lead to an inverted U-shaped relationship between greater IPR strength and total development expenditures, or overall development prospects, when higher knowledge levels are not too unlikely from an ex ante perspective. We show this numerically in Section 4.

The rest of the paper is organized as follows. In Section 2, we set up our model, describing its notation, timing and the protocols of bargaining processes involved in knowledge licensing. In Section 3 we characterize the equilibrium choices of modes of licensing, and surplus sharing, across RU and her licensee DU. In Section 4 we study comparative statics with regard to the degree of protection of intellectual property rights. Section 5 discusses related literature. Section 6 concludes.

2 The model

2.1 The setup

There are three risk neutral agents: a research unit RU and two competing development units DU_1 and DU_2. These parties undertake research (by RU) and development (by DUs) to create a new product. The investments in research and development are sequential. First, RU produces knowledge K. This knowledge has no value per se, but is an input in the development stage which may result in the creation of a new product. If only one DU develops successfully, he obtains a monopoly rent of $V = 1$ in the product market. If two DUs succeed in development, they compete a la Bertrand and both get zero rents.

In this paper, we do not focus on the knowledge generation process and take the level of knowledge $K \in [0, 1]$ as given. We assume K to be the outcome of an exogenous random

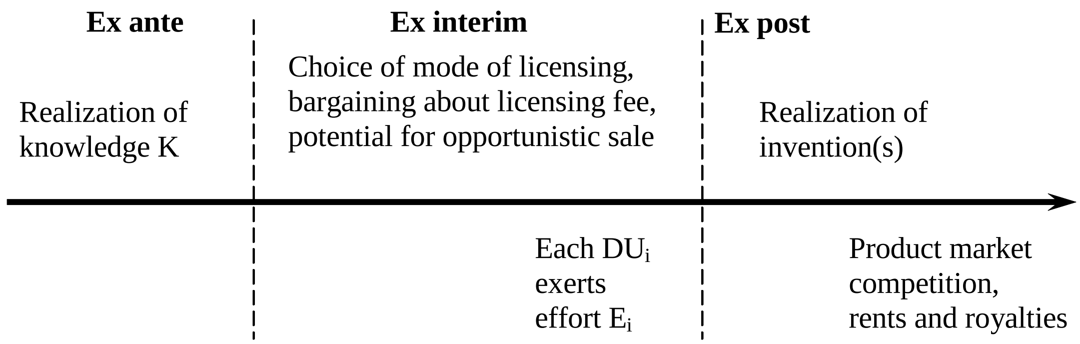

Figure 2: Timing.

process with a density known ex ante.

For each DU, his probability P of successful development is a function of his acquired knowledge and subsequent non-contractible development effort $E \in [0, 1/2]$:[8]

$$P = p(K, E) = \sqrt{2KE}. \tag{1}$$

The development effort E is measured in terms of its cost. These are assumed non-verifiable. Knowledge is metrized in terms of the maximum probability of successful second-stage invention it could lead to. The constraint $E \leq 1/2$ is to make sure that this probability cannot exceed 1. However, in all equilibria considered in the paper $E \leq K/2 = \arg\max_E \left[\sqrt{2KE} - E\right]$, so that this constraint is never binding.

2.2 Timing and assumptions

The timing of events is presented in the Figure 2.

1. Ex ante.

   RU obtains knowledge K.

2. Ex interim.

   The parties choose the mode of licensing of RU's knowledge, and bargain on the licensing fee. The bargaining game in each mode, with and without patenting, is described in detail below.

   The two alternative modes of knowledge licensing evolve as follows.

   (a) Open mode.

   A patent (IPR) is registered, so that RU can commit to sell her knowledge to one party only. This requires RU describing her knowledge publicly which leads to a partial leakage of her knowledge; an exogenous proportion $L_o \in [0, 1]$ of the knowledge K is divulged to both DUs. Both DUs also infer the level of RU's knowledge K from this description. The firm i that licenses the full content of RU's knowledge pays RU a lump-sum fee F_o and chooses development effort E_i; the respective probability of development is $P_i = p(K, E_i)$. The other firm j chooses effort E_j, and his probability of development is $P_j = p(L_o K, E_j)$. These effort choices $\{E_i, E_j\}$ form Nash equilibrium strategies in the game between the two DUs with ex post payoffs contingent on their final inventions being described below.

(b) Closed mode.

Knowledge disclosure occurs through a private sale to one of the DUs (randomly chosen by an independent RU). The parties bargain about a licensing contract, with its payoffs contingent in part on DU_i's post-invention revenues. As the ex post outcome is binary ($V = 1$ or $V = 0$), this contract includes only two variables: a lump-sum transfer F_c from DU_i to RU and RU's share s (e.g. via royalties) in DU_i's ex post revenues.

To initiate the bargaining RU provides a description of her knowledge, which is sufficient for DU_i to infer its level K. This description also leads to some partial leakage of RU's knowledge, $L_c K$, to DU_i, where $L_c \in [0, 1]$ is also an exogenous parameter. After RU and DU_i agree on the terms of disclosure, RU reveals the full content of her knowledge to the licensee DU_i, and DU_i chooses his development effort E_i. We denote P_c as his corresponding probability of invention.

RU could also sell her knowledge to DU_j subsequently. In this opportunistic deviation by RU, she would first describe her knowledge causing leakage $L_c K$ to DU_j. If they agree on a fee for RU disclosing the full content of her knowledge, DU_j would then choose the probability of development P_d (where d stands for 'deviation') given the DU_i's choice of P_c. If RU and DU_j failed to agree upon the licensing fee, DU_j would develop on the basis of leaked knowledge; in this case we denote his choice of probability of invention as $\widetilde{P}_d$. By choosing the share s appropriately, DU_i will try to preclude RU's knowledge disclosure to DU_j. If s is sufficiently high, RU could be interested in protecting DU_i's ex post rents from competition; we characterize when this is feasible.

3. Ex post.

Successful developers compete a la Bertrand. If only one DU invents successfully, he obtains a monopoly rent of $V = 1$. If both develop successfully then both get zero

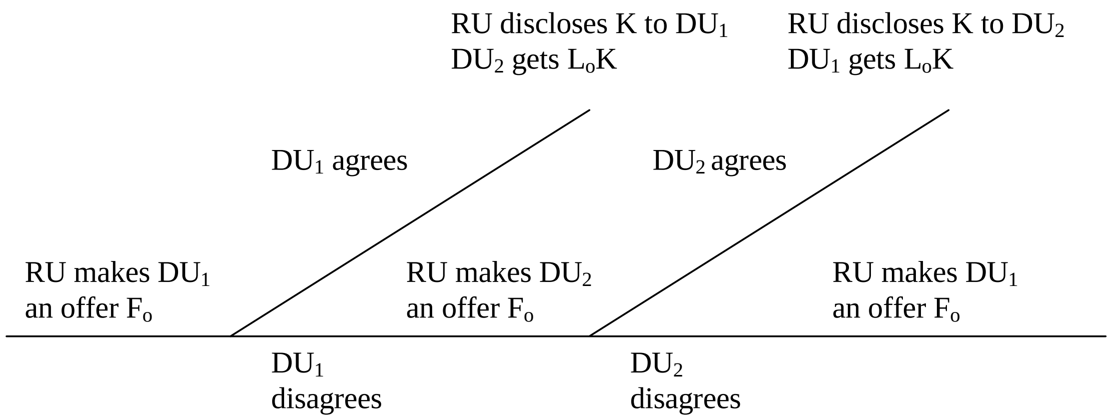

Figure 3: Bargaining in the open mode.

$V = 0$, which is also their payoff if neither invents.

We assume equal bargaining power in bilateral bargaining between a DU and an RU.

In our view, it is at least a plausible working hypothesis that proportions of enabling knowledge leaked to potential licensees in private L_c and patent-based L_o descriptions may be very similar – especially for an interim innovative idea. For such innovations the final details of its implementation (e.g. the precise product or manufacturing process) remain unclear. While the description of codifiable aspects of an innovation in a patent would preclude their replication (via resale), pre-licensing description of the idea in a closed-mode negotiation, to establish its potential, might not need such aspects to be disclosed prior to reaching agreement on a licensing contract. If that is not the case, then L_c is likely to exceed L_o.[9]

2.3 Bargaining in the open mode

The multilateral bargaining game in the open mode is similar to the one in Bolton and Whinston (1993). RU and the DUs bargain about full disclosure of knowledge K. After patenting, RU makes an offer to DU$_i$. The offer specifies the payment F_o for the exclusive disclosure of knowledge K to DU$_i$. DU$_i$ either accepts or declines the offer. In the former case, DU$_i$ develops on the basis of K, while the competing DU$_j$ only has access to the leaked knowledge LK. If DU$_i$ declines RU's offer, RU makes an offer to DU$_j$ and so on. We analyze an infinite horizon bargaining game, with parties having a common discount rate $\delta \to 1$.

Once the agreement on the terms of disclosure is reached, $DU_{1,2}$ choose their post-licensing levels of development effort $E_{1,2}$ (equivalently, their probabilities of successful development $P_{1,2}$), as detailed above.

We rule out patented sales to both DUs. We shall show that in the resulting tripartite bargaining (e.g., see Bolton and Whinston, 1993) this is always dominated from RU's point of view by an exclusive knowledge sale to one DU. The RU is better-off with the exclusive sale, even when licensing to both DUs may increase total surplus ex interim. The rationale is that in the latter case RU would only get half of this total surplus, while under an exclusive sale the two DUs compete a la Bertrand for a single license, modulo the DUs' disagreement option of development based on leaked knowledge. A formal proof is provided in Section 3.

2.4 Bargaining in the closed mode

RU randomly chooses DU_i to arrange a private sale. The bargaining in the closed mode is a conventional bilateral alternating offer game as in Rubinstein (1982): RU makes an offer of $\{s, F_c\}$; if DU_i declines, it makes a counteroffer etc.

The resulting sharing of payoffs must take into account the outside options of both RU and DU_i. RU has the option of patenting her knowledge for open mode licensing. Once the IPR is registered, in the form of a patent, the two parties cannot return to private sales. RU would therefore not enter into a closed mode sale unless it would generate a total expected payoff for her $(F_c + sP_c)$ that at least equals her equilibrium licensing fee F_o in the open-mode.

Similar logic applies to DU's outside option. As we will show below, in equilibrium F_o is such that both DUs obtain equal net payoff in the open mode licensing. Hence either of them would reject any closed-mode offer from the RU below what the non-licensee DU would have in a patented sale based on the enabling knowledge L_cK that is disclosed to DU_i in the course of closed-mode negotiations. If L_c equals L_o, either party can force reversal to the open mode during bargaining. We describe below how these concerns affect their equilibrium choices over the modes of licensing.

2.5 Interim payoffs

We will denote as T_c and T_o the total equilibrium ex interim expected surplus of RU cum the licensee DU obtaining the full knowledge in the closed and in the open mode, respectively. We will denote as $U_{oi}(P_i, P_j; K)$ the expected ex interim payoff of this DU in the development race in the open mode, whereas the other DU_j chooses probability of invention P_j to maximize $U_{oj}(P_j, P_i; L_oK)$. According to (1), DU_i's effort cost is $E_i =$

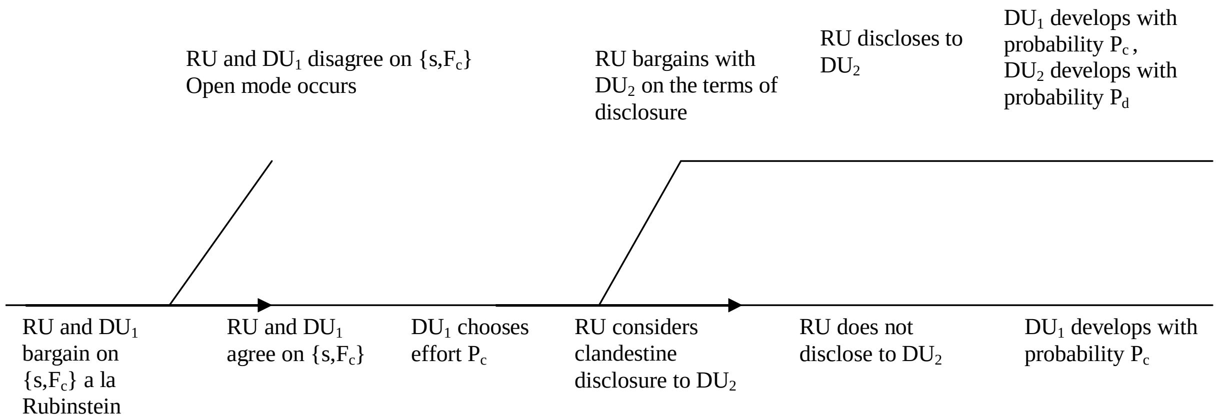

Figure 4: Bargaining in the closed mode. Arrows indicate the equilibrium path.

$P_i^2/(2K)$ so that in the open mode

$$U_{oi} = [(1 - P_j)P_i - P_i^2/(2K) - F_o] \tag{2}$$

which increases in K and decreases in P_j. Since F_o is paid before the development effort is chosen, the DU$_i$'s payoff (2) is maximized at $P_i = K(1 - P_j)$. The competing DU$_j$ develops on the basis of leaked knowledge L_oK; he maximizes his payoff

$$U_{oj} = [(1 - P_i)P_j - P_j^2/(2L_oK)]$$

by choosing $P_j = L_oK(1 - P_i)$.

Correspondingly, in the closed model of knowledge sale the licensee DU obtains:

$$U_c = [(1 - s)P_i - P_i^2/(2K) - F_c] \tag{3}$$

where P_c is the optimal choice of P_i in this mode. The RU's payoff consists of the royalty sP_c and the cash payment F_c made before the choice of development effort. For simplicity, we assume that the non-licensee DU$_j$ has no development capabilities in equilibrium. The licensing terms, F_c and s, are chosen via bilateral bargaining between RU and DU$_i$; the contract terms incentivise RU not to sell her knowledge do DU$_j$.

2.6 Choice over licensing modes

In essence, the bargaining structure above implies that the choice of the mode would be made according to whether or not the total (subgame-perfect) equilibrium payoffs summed across the RU and her licensee DU, $T_{o,c}$ is higher in the open or the closed mode of licensing, with the following two main exceptions.

If L_c is higher than L_o by a sufficient amount, then RU may not make a closed-mode offer. Indeed, in the closed mode the licensee DU_i would not pay RU more than what he would gain from having the whole knowledge K and his rival DU_j none, as compared to DU_i having knowledge L_cK and DU_j having K, as in Anton and Yao (1994). This payment to RU could be below F_o, even when $T_c > T_o$.

The other case is where K is such that the level of RU's required revenue share s to ensure an exclusive closed-mode sale is so high that RU has to make a lump-sum payment to her licensee $DU_i : F_c < 0$. As RU's wealth constraint precludes her making the payment, the parties may have to may patent the knowledge even though $T_c > T_o$. This happens whenever $T_c - sP_c < T_o - F_o$. We consider further implications of this case in a companion paper.

3 Equilibrium outcomes

In this Section we characterize the equilibrium payoffs of the RU and the DUs under the alternative modes of disclosure at the ex interim stage. First, we derive the joint surplus of the RU and her licensee DU_i in the open and closed modes of disclosure, $T_o(K, L_o)$ and $T_c(K, L_c)$, respectively. Then we study the outcome of bargaining and describe the division of this surplus between RU and DU_i.

3.1 Open mode

If a patent is registered then (the exclusive licensee) DU_i pays RU a licensing fee F_o and obtains knowledge K. At the same time, knowledge L_oK is leaked to the public domain, so the competing DU_j can also engage in the development contest. The joint surplus of RU and DU_i will therefore equal $T_o = [U_{oi} + F_o]$; see (2). The competing DU_j will use the leaked knowledge L_oK, and will therefore receive $[(1 - P_o)\widetilde{P}_o - \widetilde{P}_o^2/(2L_oK)]$. Here the probabilities $\left\{P_o, \widetilde{P}_o\right\}$ satisfy the Nash equilibrium conditions:

$$P_o = \arg\max_p \left[(1 - \widetilde{P}_o)p - p^2/(2K)\right] = K(1 - \widetilde{P}_o),$$
$$\widetilde{P}_o = \arg\max_q \left[(1 - P_o)q - q^2/(2L_oK)\right] = L_oK(1 - P_o).$$

For each pair of K and L_o the solution is unique:

$$P_o = \frac{K - L_oK^2}{1 - L_oK^2}; \quad \widetilde{P}_o = \frac{L_oK - L_oK^2}{1 - L_oK^2}. \tag{4}$$

Note that P_o is increasing in K for all L_o, while $\widetilde{P}_o$ is initially increasing and then decreasing in K, approaching the limit of $\widetilde{P}_o = 0$ as $K \to 1$ for all $L_o < 1$. Indeed, knowledge has two effects on incentives to exert effort. There is a positive direct effect, and there is a negative indirect effect that works via strategic response to the competing DU. The direct effect is stronger for the licensee DU as it uses full rather than leaked knowledge. However, the magnitude of the indirect effect is stronger for the non-licensee DU_j for higher levels of knowledge K.

The RU's fee F_0 is determined as the outcome of the sequential offer bargaining game described in the Section 2.3 above, emulating Bolton and Whinston (1993).

Lemma 1 *In the open mode the licensing fee sets the licenses DU_i to his disagreement payoff: either DU obtains the net payoff of* $U_o \triangleq U_{oj}\left(\widetilde{P}_o, P_o; L_o K\right) = \left[(1-P_o)\widetilde{P}_o - \widetilde{P}_o^2/(2L_oK)\right]$, *while RU obtains* $F_o = \left[\{P_o(1-\widetilde{P}_o) - P_o^2/(2K)\} - \left\{(1-P_o)\widetilde{P}_o - \widetilde{P}_o^2/(2L_oK)\right\}\right]$ *from* DU_i.

Proof. The unique subgame perfect equilibrium (SPE) in the bargaining game is as follows. RU always offers the fee above to DU_i. DU_i accepts the offer, because he knows that DU_j will agree to the payoff U_o after paying this fee when she is offered the license next. Similar reasoning holds for DU_j.

Indeed, let us reproduce the proof in Bolton-Whinston (1993). Conventional arguments imply that in SPE, the RU's licensing offer is accepted by DU_i in the first round. The uniqueness follows from the fact that RU chooses the continuation subgame that provides her with the highest payoff. In order to calculate the licensing fee, let us denote $\{u_i, u_j\}$ the DUs' payoffs in the SPE; here i is the DU whose turn is to be made the offer, and j is the other one. Then the maximum possible fee DU_i would pay is $F_o = T_o - \delta u_j$; if $T_o - F_o < \delta u_j$, the DU_i would turn down the offer. Therefore RU's equilibrium strategy is to offer F_o. As DU_i accepts RU's offer in equilibrium, the non-licensee DU gets $u_j = U_{oj}\left(\widetilde{P}_o, P_o; L_oK\right)$. As $\delta \to 1$, we obtain the fee above. ■

Essentially, this bargaining results in Bertrand competition between the two DUs: RU extracts all the additional surplus of the licensed DU, making his participation constraint bind. The intuition for this result is related to the nature of patented IPR: RU holds full rights for an exclusive sale, and can choose whom to sell her knowledge to.

Using (4) we obtain the equilibrium payoffs of the RU and DU:

$$T_o = \frac{K(1-L_oK)^2}{2\left(1-L_oK^2\right)^2}; \quad F_o = \frac{K(1-L_o)}{2\left(1-L_oK^2\right)}; \; U_o = T_o - F_o = \frac{K(1-K)^2L_o}{2\left(1-L_oK^2\right)^2}. \tag{5}$$

Both $T_o(K, L_o)$ and $F_o(K, L_o)$ increase in K and decrease in L_o for all $K, L_o \in [0,1]$. On the other hand, either DU's payoff U_o *increases* with L_o. Indeed, the licensee DU receives her reservation utility which is equal to the payoff of a non-licensed DU; the latter clearly

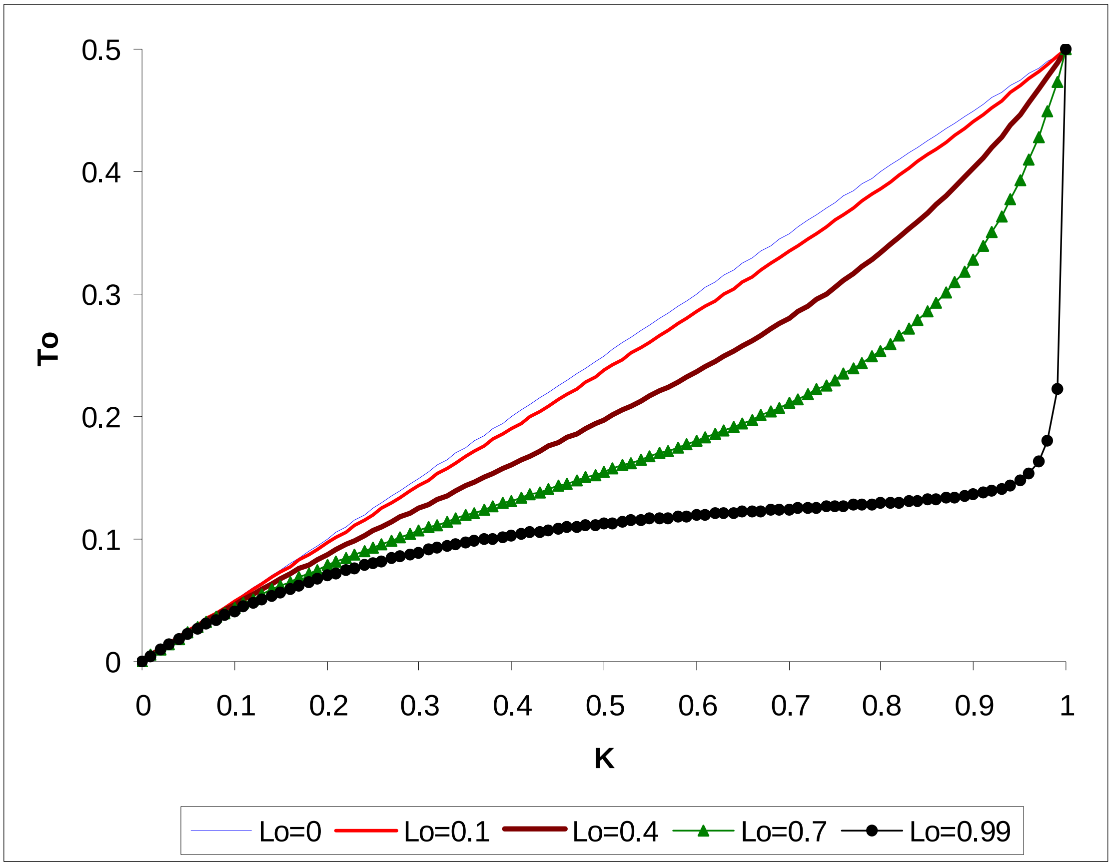

Figure 5: The joint surplus of RU and DU_i in the open mode as a function of knowledge level K for different values of leakage L_o.

increases when the proportion of knowledge that is leaked increases. However, unlike T_o and F_o, each DU's payoff U_o is first increasing and then decreasing in K, approaching zero as $K \longrightarrow 1$ for all $L_o < 1$. This explains why the joint surplus T_o is first concave and then convex in K (see Figure 5).

Remark 1 *RU is better off with an exclusive sale rather than selling knowledge twice. Indeed, suppose that RU decides to sell knowledge to both DUs. In equilibrium each DU develops with probability* $P_o = K/(1+K)$*; gross of the licensing fee, each DU's surplus is* $\frac{K}{2(1+K)^2}$*; the solution is equivalent to (4) and (5) in the limiting case* $L_o = 1$*. Following the proof in Bolton and Whinston (1993) for the case of sales to both downstream firms, we find that each DU pays RU* $\frac{1}{2}\left(\frac{K}{2(1+K)^2} - U_{oj}\left(\widetilde{P}_o, P_o; L_o K\right)\right)$*. Overall, RU collects*

$$\left(\frac{K}{2(1+K)^2} - \frac{K(1-K)^2 L_o}{2\left(1-L_o K^2\right)^2}\right) = \frac{K}{2}\frac{1-L_o}{1-L_o K^2}\frac{1-L_o K^4}{(1+K)^2\left(1-L_o K^2\right)} < \frac{K}{2}\frac{1-L_o}{1-L_o K^2} = F_o.$$

Therefore, even though the total DUs' surplus is larger, RU can only capture a small part of this surplus and is therefore not willing to sell to both DUs.

3.2 Closed mode

If the contracting parties do not register a patent but choose disclosure via a closed sale, there is no leakage to outsiders in equilibrium. However, in order to provide RU with incentives not to disseminate knowledge to the competing DU_j, DU_i has to give away a sufficient share s of his ex post revenues in royalties to RU, so that:

$$[sP_c - sP_c(1-P_d)] \geq \left[\left\{(1-P_c)P_d - P_d^2/(2K)\right\} - \left\{(1-P_c)\widetilde{P}_d - \widetilde{P}_d^2/(2L_cK)\right\}\right] . \quad (6)$$

where P_c is chosen by the licensee DU_i and $\left\{P_d, \widetilde{P}_d\right\}$ are the potential choices of the other DU_j if the RU attempts to sell knowledge to her. P_d is chosen by DU_j if she has full knowledge, and $\widetilde{P}_d$ is her choice with leaked knowledge L_cK.

For a given share s, the left-hand side in (6) is the reduction in the RU's payoff due to opportunistic disclosure to DU_j. The right hand side is the maximum licensing fee that RU may extract from DU_j in case she decides to disclose to him after licensing her knowledge to DU_i. The logic of calculating this licensing fee is very similar to the one in open sales: since the process of negotiating the fee results in a partial leakage of knowledge L_cK, RU can obtain from DU_j at most the expression in the right-hand side. If and only if (6) is violated, there exists a fee that DU_j will be willing to pay and RU will be willing to accept in exchange for the clandestine second sale.

RU's incentives for exclusive disclosure come from the fact that selling the knowledge to a competing DU_j dilutes the DU_i's expected payoff, and thus reduces the value of RU's royalty stake from sP_c to $sP_c(1-P_d)$ as described in the left-hand side of (6).

While giving a sufficiently high share of ex post revenues to RU rules out opportunistic disclosure, it comes at a cost of lowering the licensed DU's incentives to apply effort. Indeed, by solving for optimal effort of DU_j and DU_i we find that P_c decreases in s :

$$P_d = \arg\max_p \left[(1-P_c)p - p^2/(2K)\right] = K(1-P_c); \quad (7)$$

$$\widetilde{P}_d = \arg\max_q \left[(1-P_c)q - q^2/(2L_cK)\right] = L_cK(1-P_c); \quad (8)$$

$$P_c = \arg\max_p \left[(1-s)p - p^2/(2K)\right] = K(1-s). \quad (9)$$

In equilibrium, RU and DU_i will choose the minimum possible $s \in [0,1]$ that satisfies (6). Cancelling the sP_c terms in the left hand side of (6) and using (7) and (8), we rewrite the incentive constraint as

$$sP_cP_d \geq \left[K(1-P_c)^2/2 - L_cK(1-P_c)^2/2\right]. \quad (10)$$

By substituting (7) and (9) into (10), we obtain a quadratic inequality

$$sK(1-s) \geq (1-K(1-s))\,(1-L_c)/2. \tag{11}$$

Lemma 2 *A mechanism for a closed knowledge sale, which is incentive-compatible for no further disclosure by the RU, requires RU to be given a (minimum) share $s = s^*(K; L_c)$ in her licensee DU's post-invention revenues, where $s^*(K; L_c)$ satisfies:*

$$s^*(K;L_c) = \left(1 + L_c - \sqrt{(1+L_c)^2 - 8(1-L_c)(1/K-1)}\right)/4 < 1/2. \tag{12}$$

The licensee DU develops with probability $P_i = P_c = K(1 - s^*(K; L_c))$, the other DU does not develop. This closed mode licensing is only feasible if such $s^*(K; L_c)$ exists, i.e., whenever $K \geq \widehat{K}(L_c)$, where

$$\widehat{K}(L_c) = \left(1 + \frac{(1+L_c)^2}{8(1-L_c)}\right)^{-1}. \tag{13}$$

Proof. The proof is straightforward. Let us first consider the case $L_c < 1$. For $K = 0$, the incentive constraint (11) does not hold. If $K > 0$, the inequality turns into

$$2s^2 - (1+L_c)s + (1-L_c)(1/K-1)] \leq 0.$$

Since the parties are interested in finding the lowest s that still satisfies (6), we need to solve for the smaller root. The real root exists if and only if $K \geq \widehat{K}(L_c)$ where $\widehat{K}(L_c)$ is given by (13). In this case, the smaller root is (12).

If the leakage is complete $L_c = 1$ (as in Anton and Yao, 1994), the incentive constraint is always satisfied. Indeed, second sale would never be tempting for the RU, as she would not get any revenue from DU_j. In this case formulas (12) and (13) still hold: $\widehat{K}(1) = 0$, and $s^*(K; 1) = 0$.

The second sale never happens in equilibrium. Indeed, suppose that the contract $\{s, F_c\}$ is such that RU decides to sell knowledge to DU_2 as well; it is easy to show that in this case the optimal royalty is trivial $s = 0$. Essentially, parties go back to the open mode where RU sells to both DUs. As discussed above, this outcome is dominated by the *exclusive* patented sale. ■

This result is intuitive; the monopoly development rents of DU_i suffice to overcome RU's temptation to disclose to the other DU whenever the level of interim knowledge is high enough. If $K < \widehat{K}(L_c)$ then the private disclosure to one DU cannot be arranged because of the adverse incentive effect on DU's effort. In order to increase the RU's stake, DU_i gives RU a higher share s. However, as s increases, DU_i's effort decreases, so that P_c falls. Hence, the competing DU_j is prepared to pay more for the knowledge: the lower P_c, the higher the payoff to DU_j's effort. At lower levels of interim knowledge $K < \widehat{K}(L_c)$, RU's returns to opportunistic disclosure (the right-hand side in (6)) increase in s so rapidly that the benefits of keeping DU_i a monopoly (the left-hand side in (6)) never catch up with it. Since $P_c = K(1-s)$, sP_c reaches its maximum at $s = 1/2$, implying $s^*(K; L_c) \leq 1/2$.

The closed mode is feasible when leakage L_c is *high*, since RU's payoff from a deviant second sale declines when L_c increases. Indeed, $\widehat{K}(L_c)$ decreases in L_c from $\widehat{K}(0) = 8/9$ to $\widehat{K}(1) = 0$.

Whenever the closed mode is incentive-compatible, the RU's share $s^*(K; L_c)$ decreases with K and with L. The higher K, the higher the payoff to the monopoly development. Since higher K increases the probability of successful development, if there were two competing developers there would be a high cost of ex post rent dissipation due to Bertrand competition. Therefore RU has incentives not to disclose to the second DU even if her share s is small. Furthermore, the value of RU's stake in post-invention revenues sP_c *decreases* in K.[10] Clearly, whenever $s = s^*(K; L_c)$ exists, it decreases in K, and so that right-hand side of (11) decreases in K. Therefore the left-hand side $sK(1-s) = sP_c$ also *decreases* in K. The joint surplus of RU and DU_i

$$T_c = P_c - P_c^2/(2K) = K\left(1 - s^*(K; L_c)^2\right)/2 \tag{14}$$

is increasing in K. This joint surplus is concave in K and approaches $K/2$ as K increases; although $s^*(K; L_c)$ decreases in K, its rate of decrease slows down at higher levels of K. Indeed, $s^*(K, L_c)$ is convex in K as $s^*(K, L_c)$ is a negative linear function of a square root of concave function of K.

Unlike in the open mode where the joint surplus of RU and the licensed DU_i decreases in leakage L_o, joint surplus T_c in the closed mode *increases* with L_c. If L_c is higher, RU can receive less from the competing DU_j; her opportunistic disclosure is less attractive. Hence, DU_i can give RU a lower share of ex post revenues; therefore his development effort and probability of successful development P_c rise. This also leads to a higher joint surplus $T_c(K, L_c)$ when L_c rises, since the share $s^*(K; L_c)$ falls (see equation (14)).

Remark 2 *The contract above conditions payments from DU_i to RU on DU_i's ex post revenues. We do not consider a richer contractual environment where RU's fees are contingent on discovery by the other DU_j (like in Anton and Yao, 1994). Such contracts are unlikely to be enforceable under standard tort law as DU_j could in principle discover the idea independently of RU. On the other hand, these contracts have only a limited impact on our results. Indeed, suppose that instead of the stake s in DU_i revenues, RU has to pay a penalty φ (e.g. to a third party) in case DU_j invents.*[11] *RU's wealth constraint implies $\varphi \leq F_c$, where F_c is the lump-sum fee paid by DU_i to RU. The strongest incentives are*

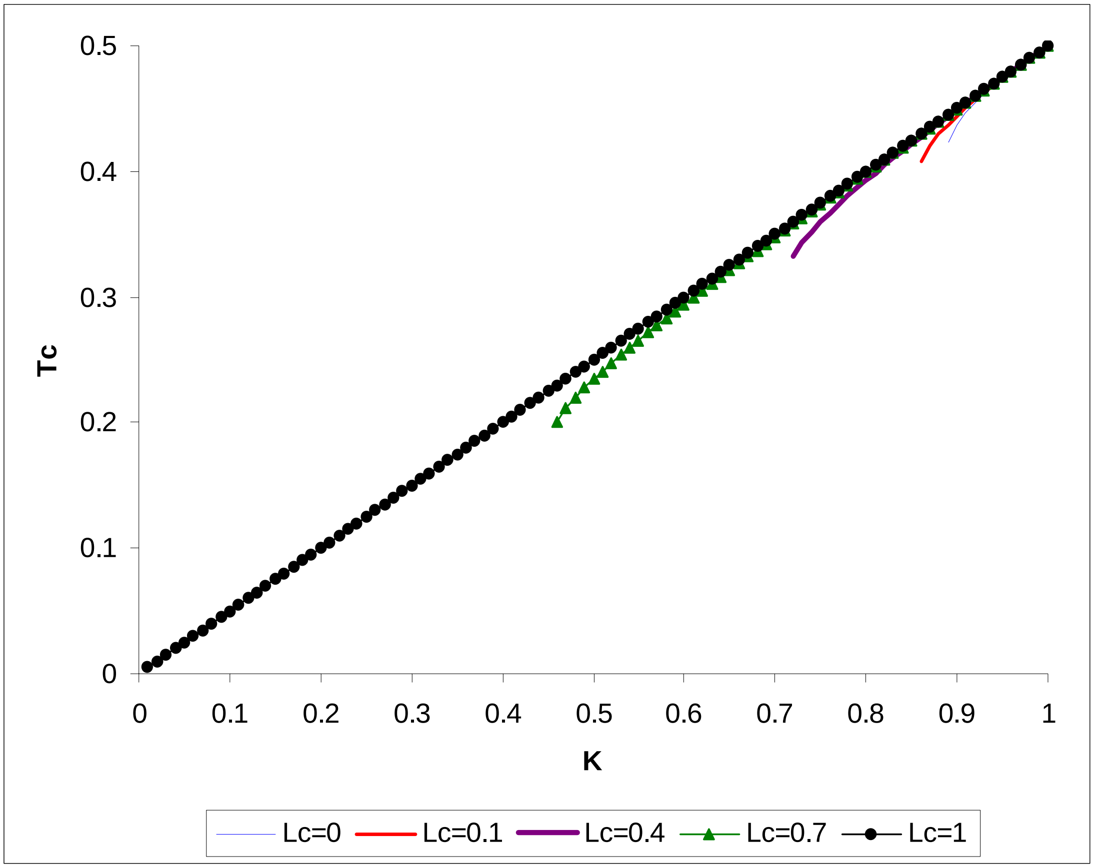

Figure 6: The joint surplus of RU and DU$_i$ in the closed mode as a function of knowledge level K for different values of leakage L_c.

provided when $\varphi = F_c$ hence the left hand side of the incentive compatibility constraint (6) becomes $F_c P_d$. This implies $F_c \geq (1 - L_c)(1 - K)/2$. Such contracts are not individually rational for DUi whenever $K < (1 - L_c) / (2 - L_c)$ (for these K the DU's payoff $T_c - F_c$ is negative). Also, for $K < (1 - L_c) / (13/8 - L_c)$, DU$_i$ strictly prefers the contract with positive s.

3.3 The choice of the mode of disclosure

In this Section we show that the closed mode dominates the open mode if L_o, L_c, or K are sufficiently high.

If the leakages L_o, L_c are low, the open mode dominates the closed mode. Indeed, if L_o is low, the joint surplus of RU and DU$_i$ is not undermined by the competing development unit DU$_j$; ex interim joint surplus T_o is close to its maximum $\max_p[P - P^2/(2K)] = K/2$. Moreover, for low L_c the risk of opportunistic disclosure in the closed mode is high, so DU$_i$

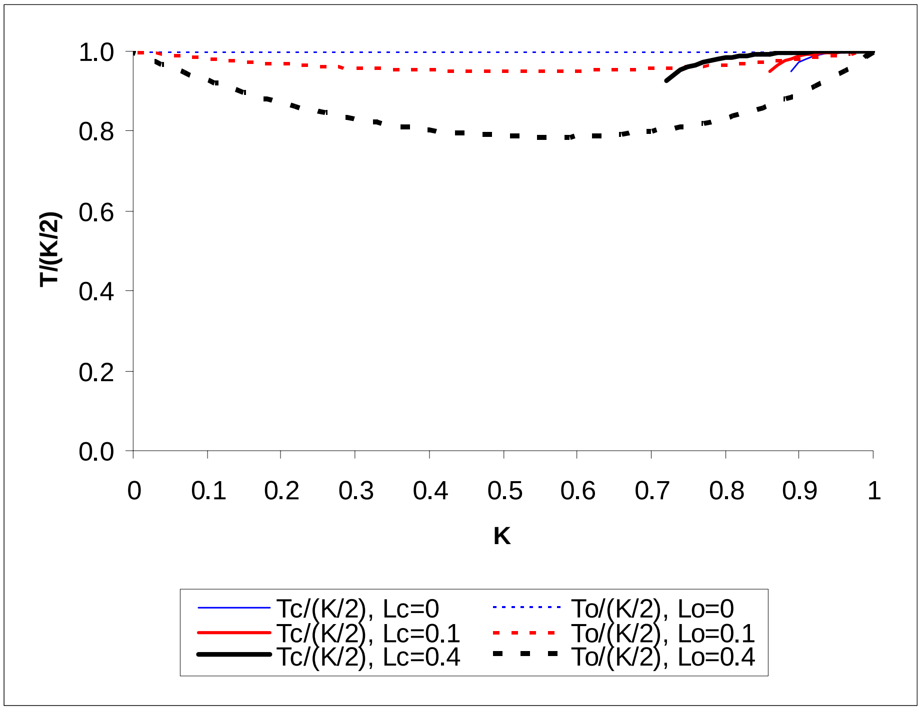

Figure 7: The graph presents joint surplus as a share of $K/2$ (i.e. surplus if there were no leakage in the open or no threat of second sale in teh closed mode). In the closed mode, $T_c/(K/2)$ is concave in K, while in the open mode $T_o/(K/2)$ is convex in K.

has to give RU a very high revenue share; hence his probability of successful development is lowered. As the leakage in either mode rises, open sales become less efficient, while closed sales produce a higher surplus to RU and licensee DU$_i$.

The closed mode is also more efficient for high K. Consider the case where K is sufficiently close to 1. If $K \to 1$, then (5) and (14) imply $T_c \to [\frac{1}{2}K - (1-K)^2 \frac{K}{2}\left(\frac{1-L_c}{1+L_c}\right)^2]$; $T_o \to [\frac{1}{2}K - (1-K)\frac{L_o}{1-L_o}]$. Therefore for any $L_o > 0$, there exists a range of K sufficiently close to 1 such that $T_c > T_o$. The higher K the more valuable the monopoly DU's rent, hence the threat of opportunistic disclosure in the closed mode is less important. On the other hand, if K is low $K < \widehat{K}(L_c)$, then a private sale to one DU is infeasible ($s^*(K; L_c)$ does not exist), so the open mode is chosen.

Proposition 1 *If the closed mode of knowledge sale is more efficient for some $\widetilde{K}$, then it is also more efficient for all $K \geq \widetilde{K}$. There exists a $K^*(L_o, L_c) \geq \widehat{K}(L_c)$ such that: $T_c \geq T_o$ for all $K \geq K^*(L_o, L_c)$, while if $K < K^*(L_o, L_c)$ the closed mode either does not exist, or is dominated by the open mode $T_c < T_o$.*

Proof. The joint surpluses in the closed and the open modes are equal to each other at

$K=1: T_c(1;L_c)=T_o(1;L_o)=1/2$. For any given $L>0$ the functions $T_c(K)$ and $T_o(K)$ may cross at most once more, at $K=K^*(L_o,L_c)<1$. At this crossing point, $T_c(K)$ grows faster than $T_o(K)$: if there is such $K^*(L_o,L_c)$ that $T_c(K^*(L_o,L_c);L_c)=T_o(K^*(L_o,L_c);L_o)$, then

$$\left(\frac{\partial T_c}{\partial K}-\frac{\partial T_o}{\partial K}\right)\bigg|_{K=K^*(L_o,L_c)}>0.$$

To prove this single crossing result, we consider the ratios of joint surplus T and the "ideal" joint surplus $K/2=\max_E\left[\sqrt{2KE}-E\right]$ in each mode (Figure 7). In the closed mode, the surplus would be $K/2$ if the opportunistic disclosure were exogenously ruled out; the ratio $T_c/(K/2)$ grows with K as the royalty share s^* declines (see (14)). Straightforward calculations prove the concavity of $\frac{T_c}{K/2}=(1-s^*(K,L_c))^2$ in K. By definition the latter equals

$$\frac{(3-L_c)^2+2\,(3-L_c)\sqrt{(1+L_c)^2-8(1-L_c)\left(\frac{1}{K}-1\right)}+(1+L_c)^2-8(1-L_c)\left(\frac{1}{K}-1\right)}{16}$$

which is a sum of concave functions of K.

In the open mode, $K/2$ is the surplus in the absence of leakage. Hence the ratio $T_o/(K/2)$ reflects the expropriation of the joint surplus by the non-licensee development. As discussed above, the non-licensee DU_j's effort first increases in K, and then falls. Not surprisingly, $T_o/(K/2)$ is convex. Indeed, $\frac{T_o}{K/2}$ is convex if $\frac{1-L_oK}{1-L_oK^2}$ is convex. But

$$\frac{\partial^2}{\partial K^2}\left(\frac{1-L_oK}{1-L_oK^2}\right)=\frac{2L_o\left[1-L_o^2K^3+3L_oK^2-3L_oK\right]}{\left(1-L_oK^2\right)^3}$$

is non-negative: the terms in brackets can be rearranged as $L_o\,(1-K)^3+(1-L_o)\,(1+L_oK^3)$.
■

For different combinations of leakage coefficients L_o,L_c, the comparison of $T_c(K;L_o)$ and $T_o(K;L_c)$ satisfies one of three cases (Figure 7). *First*, there is a case where the closed mode is more efficient whenever $s^*(K)$ exists: $T_c\geq T_o$ for all $K\geq\widehat{K}(L_c)$. In the *second* case the structure is different: at K being $\widehat{K}(L_c)$ or somewhat higher, the open mode dominates. As K increases above $\widehat{K}(L_c)$, T_c grows faster than T_o, and eventually overtakes it at some point $K^*(L_o,L_c)\in(\widehat{K}(L_c),1)$. As K increases further, the closed mode remains more efficient; $T_c>T_o$ up until $K=1$. The *third* case is that of perfect IPR protection $L_o=0$. In this case, the open mode is always optimal: $T_o=K/2>T_c$ for all $K<1$.

The parties payoff depends both on the joint surplus and on their outside options. The RU holds an outside option of switching to the open mode of knowledge sale with payoffs $\{F_o,\ T_o-F_o\}$ to RU and DU_i, respectively. Once the IPR is registered, in the form of a patent, the two parties cannot return to private sales. The DU_i's outside option is more complex. If $L_c \geq L_o$, once the closed mode bargaining begins, DU_i can ensure a payoff of $T_o(K; L_c) - F_o(K; L_c)$. Indeed, suppose that DU_i expects to receive a lower payoff. Then DU_i would reject RU's private offers. As DU_i has already obtained leaked knowledge L_cK, RU's optimal strategy is to patent the knowledge and to license it to DU_i.

In order to simplify the solution of the game, we consider the case where $L_o = L_c = L$ and return to a more general setup in the end of the section.

In the case $L_o = L_c = L$, DU's outside option becomes $T_o(K; L) - F_o(K; L)$ and the following result holds.

Lemma 3 *Suppose that $L_c = L_o$. The outcome of the bargaining game is as follows. The RU and her licensee DU_i choose the mode of disclosure that maximizes their joint surplus. If $T_o > T_c$ then the RU and DU_i's payoffs are $\{F_o,\ T_o - F_o\}$. If $T_o \leq T_c$, then their payoffs are as follows*

$$\begin{array}{ll} \left\{\frac{T_c}{2},\ \frac{T_c}{2}\right\} & \text{if } \frac{T_c}{2} \geq F_o \text{ and } \frac{T_c}{2} \geq T_o - F_o \\ \{F_o,\ T_c - F_o\} & \text{if } \frac{T_c}{2} < F_o \\ \{T_c - T_o + F_o,\ T_o - F_o\} & \text{if } \frac{T_c}{2} < T_o - F_o \end{array}$$

The formulas above are very intuitive. Efficient bargaining implies maximization of the joint surplus which is split in equal proportions as long as the outside options do not bind.[12]

Figure 8 presents K^* and $\widehat{K}$ as functions of L. Notice that both $\widehat{K}(L)$ and $K^*(L)$ decrease with L. In the areas where $K \in \left(\widehat{K}(L), K^*(L)\right)$, closed mode exists but is dominated by the open mode. The figure shows that these domains are small relative to the regions where the closed mode dominates the open mode ($K > K^*(L)$) or where the closed mode is not incentive-feasible ($K < \widehat{K}(L)$). This emphasizes the importance of analyzing the incentive-feasibility of the closed mode when studying the endogenous choice over licensing modes.

Numerical calculations show that if $L \in [0.25, 0.91]$ whenever the closed mode exists, it is chosen. If L is very low $L \in (0, 0.25)$ or L is very high $L > 0.91$, there are such levels of K when both open and closed modes exist, but the open is chosen. If L is very low, the open mode is by definition more efficient. If L is very high then the threshold level of knowledge $\widehat{K}(L)$ is so low that at $K = \widehat{K}(L)$ DU_i has to give RU a very high share in revenues which makes the closed mode suboptimal.

Indeed, in order to find L for which such a crossing $K^*(L)$ exists, we need to evaluate the sign of $T_c(K; L) - T_o(K; L)$ at $K = \widehat{K}(L)$. Substituting (13) into (12) and (14), and using (5) we find that this expression is positive whenever $D(L) = 1 - (1 + L)^2/16 - (1 - L\widehat{K}(L))^2/(1 - L\widehat{K}^2(L))^2$ is positive. An analysis of the sign of $D'(L)$ shows that function $D(L)$ is increasing if $L < 0.68$ and is decreasing otherwise. Its maximum value is positive

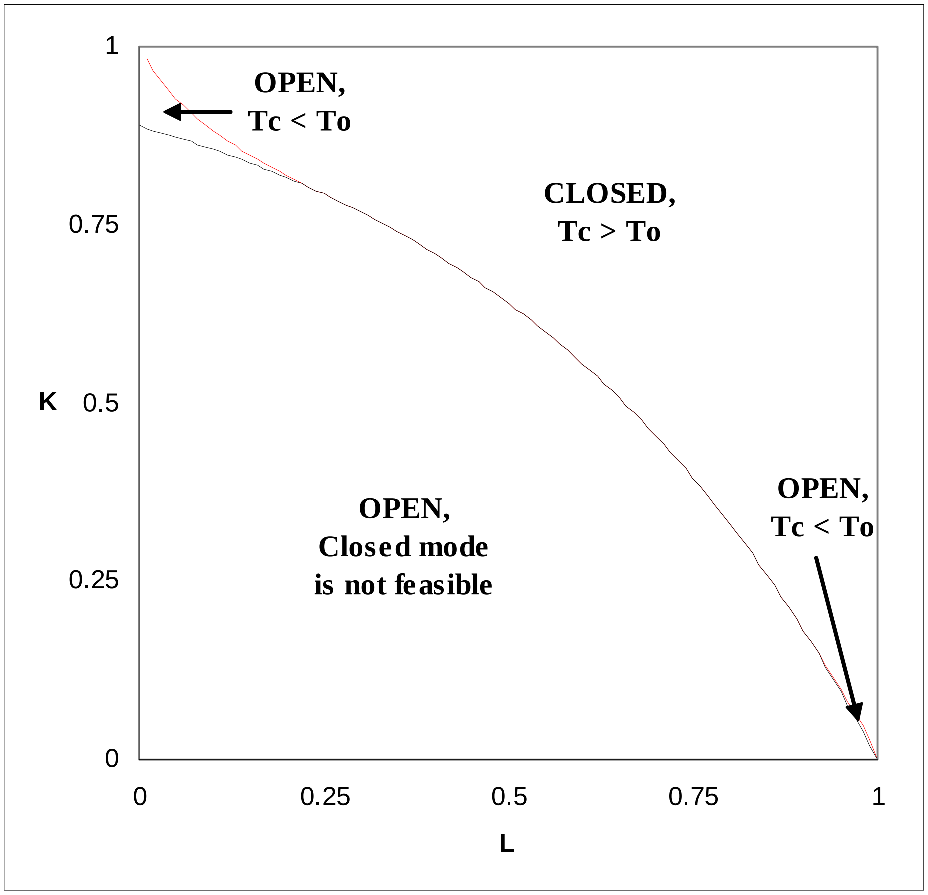

Figure 8: The optimal mode of licensing as a function of K and $L_o = L_c = L$. The (K, L) space is partitioned by two curves $\widehat{K}(L)$ (lower line) and $K^*(L)$ (upper line). For a given L, $\widehat{K}$ is the minimum level of knowledge for which the closed mode exists, K^* is the minimum level at which the closed mode dominates the open mode. The two curves coincide for all $L \in [0.25, 0.91]$.

$D(0.68) = 0.18 > 0$. It is easy to check that $D(0) < 0$ and $D(1) < 0$. Therefore there exist such $L_1 \in (0, 0.68)$ and $L_2 \in (0.68, 1)$ that $D(L) > 0$ for $L \in (L_1, L_2)$ and $D(L) < 0$ if $L < L_1$ or $L > L_2$. Simple numerical calculations yield $L_1 = 0.25$ and $L_2 = 0.91$.

Remark 3 *Given our earlier observation that the expected value of RU's royalty stake* sP_c *decreases in* K *whereas* T_c *and* F_c *increase in* K, *it may be feasible to design empirical tests of our model. Our predictions on cross-sectional correlations between the royalty (revenue-contingent) and lump-sum fees across knowledge levels are different from those implied by other considerations, e.g. risk-sharing between RU and DU.*

3.4 Extensions

RU's financial constraint. The solution above neglects the RU's ex interim financial constraint. We assume that RU's payoff consists of a stake in DU_i's revenues worth sP_c, and a lumpsum transfer F_c. If RU is financially constrained, then one needs to take into account the fact that this transfer cannot be negative, $F_c \geq 0$. The results would not change much. Straightforward calculations yield $F_c = (1-3s)(1-s)K/4$. Therefore, the financial constraint is not binding whenever $s^*(K, L_c) \leq 1/3$. If $s^*(K, L_c) > 1/3$, then there is no way to arrange a closed sale without violating RU's financial constraint: $s^*(K, L_c)$ is the lowest royalty stake that still prevents opportunistic disclosure. If RU and DU_i agree on an even higher stake $s > s^*(K, L_c)$, then the lumpsum payment $T_c/2 - sP_c$ would decrease further. Indeed, $T_c/2$ decreases in s, while $sP_c = sK(1-s)$ increases in s for all $s \leq 1/2$. Yet, even if $s^*(K, L_c) > 1/3$, the closed mode may still be chosen: if $T_c > T_o$ and $T_c - sP_c$ is above $T_o - F_o$, the DU will agree to a closed mode license with $F_c = 0$. This implies that the RU's financial constraint matters rather little for the choice of the mode.[13]

Differential leakages in open and closed mode. As discussed above, we believe that it is reasonable to assume similar leakages across the modes for interim non-marketable innovations: $L_c = L_o$. The results however hold if L_c is slightly higher than L_o. Indeed, in this case the proofs of Proposition 1 and Lemma 3 can be easily reproduced.

The less likely cases are the ones where L_c is lower or substantially higher than L_o. In the latter case there may emerge a situation where the RU's maximum payoff in the closed mode $T_c(K; L_c) - [T_o(K; L_c) - F_o(K; L_c)]$ is below her open mode fee $F_o(K; L_o)$. Expecting a low payoff in the closed mode, RU will prefer the open mode even if the joint surplus were higher in the closed mode. However, this change does not affect the "monotonicity" of the mode choice: the closed mode is still selected only for high Ks.[14]

While the case $L_o > L_c$ is less realistic, it is also covered by our analysis. Here the DU's outside option in the closed mode is less attractive and therefore RU expects to receive a higher payoff in the closed mode. Thus RU may want to stick to the closed mode as the open mode would only provide her with a low fee $F_o(K; L_o)$. However, if the total surplus is higher in the open mode, DU_i will pay RU for patenting (as the knowledge is not contractable, the payment should be contingent on the fact of patenting per se).[15]

4 IPR protection and aggregate development effort

4.1 Leakage, IPR protection, and R&D incentives

In this Section we study how the endogenous choice of the licensing mode affects the relationship between IPR protection and the aggregate development effort in the economy. Our model accounts for a number of countervailing effects, some of which have not been discussed before in the literature. For simplicity, we proxy the level of IPR protection by $1-L_o$ and the aggregate level of development investment by E_1+E_2. We consider two cases. In the first one, we assume that the leakage coefficients in the open and closed modes are the same, $L_o = L_c = L$; we have argued for the plausibility of this case above. In the second case, we let L_o vary keeping L_c constant. This comparative statics analyzes the effect of changes in patenting law on development expenditures and welfare. The qualitative results for these two cases are similar.

We do not consider the effect of RU's research effort because it is usually small compared to DU's investment; also it is often non-pecuniary and hard to measure empirically. We also study the the impact of IPR on the social welfare $1-(1-P_1)(1-P_2)-E_1-E_2$. One has to be cautious in interpreting the latter results. Unlike development expenditures, full social returns to R&D are hard to characterize in reality; this is why empirical studies focus on the relationship between IPR protection and R&D rather than social welfare (Lerner, 2001).

We first consider the role of IPR protection for a given mode of disclosure. If the knowledge is disclosed through open sales then better IPR protection (A) improves the incentives to develop for the licensee DU_i, but also (B) weakens non-licensee DU_j's incentives. Given K and L_o, the total development effort by DU_1 and DU_2 in the open mode is

$$E_o = E_i + E_j = \frac{P_o^2}{2K} + \frac{\widetilde{P}_o^2}{2L_oK} = \frac{K}{2}\frac{(1-L_oK)^2 + L_o(1-K)^2}{(1-L_oK^2)^2}.$$

Lemma 4 *In the open (patent-based) mode of knowledge sales the total development effort* E_o *either monotonically* decreases *with IPR protection* $1-L_o$ *(for* $K \leq 1/3$*) or has a U shape (if* $K > 1/3$*) with the minimum point of the U-shape* $L_o = (3K-1)K^{-2}(3-K)^{-1}$ *shifting from* $L_o = 0$ *to* $L_o = 1$ *as* K *increases from* $1/3$ *to* 1*. The social welfare in the open mode monotonically* decreases *with IPR protection* $1-L_o$*.*

Proof. One can easily show that $dE_o/dL > 0$ whenever $L_o > \Lambda(K) \equiv (3K-1)K^{-2}(3-K)^{-1}$. The right hand side $\Lambda(K)$ increases with K for all $K \in [0,1]$ with $\Lambda(1/3) = 0$ and $\Lambda(1) = 1$. Hence for all $K \leq 1/3$, effort E_o is decreasing in L_o, while for $K \in (1/3, 1)$ effort is U-shaped with the minimum point at $L_o = \Lambda(K)$.

Straightforward calculations imply that the social welfare equals $\frac{K}{2}\left(1+\frac{L_o(1-K)^2}{1-L_oK^2}\right)$ which is an increasing function of L_o. ■

This result is explained by the relative strength of the countervailing effects of IPR protection on licensee and non-licensee efforts. If IPR protection is strong ($L_o = 0$) then a small decrease in it has a greater impact on DU_j than on DU_i so the effect (B) is more important. The positive effect (A) on the licensee DU_i is relatively more important if K is high (and therefore the difference between K and L_oK is high).

In the closed mode, DU_j does not develop in equilibrium. The threat of opportunistic disclosure makes DU_i give RU a higher share in post-invention revenues which distorts DU_i's development effort. The higher the leakage L_c, the less important this threat, hence RU's incentive constraint is satisfied through a lower revenue share s. As a result, P_c and development effort decrease as intellectual property retention $(1 - L_c)$ increases for all K for which $s^*(K; L_c)$ exists.

There is yet another effect of IPR protection on the aggregate level of investment in development. If either L_o or L_c is sufficiently high, parties switch from open to closed mode which at the margin results in lower effort. Indeed, consider the case of $L_o = L_c = L$, and $L < 0.25$ or $L > 0.91$. In this case, the switching occurs at the point where $T_c = T_o$. At this point, the total cost of development is greater in the open mode: by definition, $T_c = sP_c + (1-s)P_c - P_c^2/(2K) = P_c(1+s)/2 = T_o = P_o(1-\widetilde{P}_o)/2$. Since the total effort in the closed mode $(1-s)P_c/2$ is below $P_c(1+s)/2$, it is also below $P_o(1-\widetilde{P}_o)/2+(1-P_o)\widetilde{P}_o/2$ which is the total effort in the open mode. In the case $L \in [0.25, 0.91]$, switching occurs at $K = \widehat{K}(L)$, and $T_c\left(\widehat{K}(L); L\right) > T_o\left(\widehat{K}(L); L\right)$, so more cumbersome calculations are required. Still, after substituting $K = \widehat{K}(L)$ and $s^*\left(\widehat{K}(L); L\right) = (1+L)/4$ — its maximum possible value — into expressions for total effort in open and closed mode we find that switching to the closed mode reduces total effort, at the level of knowledge $K = \widehat{K}(L)$.[16]

To summarize, we have

Proposition 2 *There are four effects of stronger IPR protection in the open mode and of straonger intellectual property retention in the closed mode on the total effort by DUs: (A) effect on the licensee's effort in the open mode (negative effect of L_o); (B) effect on the non-licensee's effort in the open mode (positive effect of L_o); (C) effect on the DU's effort in the closed mode (positive effect of L_c); (D) effect of switching from closed to open mode (negative effect of either L_o or L_c). The latter two effects are associated with the closed mode and are therefore relatively more important for higher knowledge levels K, and for higher levels of knowledge leakage (L_o or L_c).*

As shown above in Lemma 4, in the open mode total non-contractible development expenditures as a function of $(1 - L_o)$ may be monotonic or U-shaped, but may never have an inverted U-shape. Therefore an "inverted U-shape" relationship between these cannot be produced by the effects (A) and (B) alone. Once the closed mode is introduced, so that the effects (C) and (D) are added, the inverted U-shape may indeed emerge for a broad range of parameters. Suppose that the following conditions hold: the outcomes in the open mode mostly result in a negative effect of IPR protection on the development expenditures; effect (B) prevails over (A). In the closed mode, positive effect (D) dominates negative effect (C). Both possibilities arise when the prospects for higher levels of K are not too high. Then as IPR protection declines from perfect, the development expenditures first rise (open mode effect); when IPR protection becomes sufficiently weak, the mode switching effect (D) is more important.

The impact of leakage on the social welfare measure also consists of the effects in the open mode, the effect in the closed mode and the mode switching effect. Lemma 4 implies that the welfare in the open mode increases with L_o. It is also easy to show that the welfare in the closed mode increases with L_c (in the closed mode, the social welfare is equal to T_c). The mode switching effect, however, works in the opposite direction; the greater leakage L_c and the weaker the IPR protection in the open mode, the lower average welfare. Indeed, at the margin, the welfare in the open mode is greater. As shown in the proof of Lemma 4, the welfare in the open mode is above $K/2$ while in the closed mode the welfare is always below $K/2$.

4.2 A numerical example

In this section we illustrate the Lemma and Proposition above with a numerical example. In order to capture the effect of 'going public' (D), our example has to depart from studying the relationship at a given K; rather, we consider a continuous distribution of different knowledge levels K. For simplicity's sake, we consider a family of exponential distributions on $K \in [0, 1]$:

$$g(K) = \frac{\lambda e^{-\lambda K}}{1 - e^{-\lambda}} \tag{15}$$

The extreme cases of this family are the uniform distribution for $\lambda = 0$ and a distribution with a mass point at $K = 0$ at $\lambda = \infty$. The higher the value of λ, the lower the average knowledge level $\mathsf{E}K = \int_0^1 K g(K) dK = \lambda^{-1} - \left(e^{\lambda} - 1\right)^{-1}$.

We will consider two cases. First, we assume $L_c = L_o$ (see the discussion in Section 2.2) will study the effect of variation in L. Here the change in L corresponds to technological variations in codifiability. In the second case, we will analyze the situation where whatever is codifiable in patents must be revealed in the closed sales to convey the level of K to the buyer (as in Anton and Yao, 1994). We therefore study the effect of change in L_o alone which reflects the changes in patent law and its implementation that essentially define what is considered codifiable.

4.2.1 Leakage and development expenditures

We first consider the case $L_o = L_c = L$. Figure 9 shows the relationship between L and the aggregate development expenditures for different values of λ, averaged out over $K \in [0,1]$ according to the density function (15). We present the equilibrium level of investment where the mode of disclosure is chosen as described above, i.e., on the basis of higher ex interim joint surplus of the RU cum her licensee DU_i. In order to understand the incremental importance of the effects (C) and (D), we also plot the total development expenditures, summed across DU_1 and DU_2, in the open mode (as if the closed mode were exogenously ruled out).

Let us first consider the effect of IPR protection on the licensed and non-licensed DUs' development expenditures in the open mode. In Figure 9 the effects (A) and (B) can only produce either a monotonic (increasing for low λ, decreasing for high λ) or a U-shaped relationship (for intermediate values of λ). This is consistent with Lemma 4.

Once we consider both modes of disclosure and allow for the effects (C) and (D), the relationship between $[E_1 + E_2]$ and $(1 - L)$ changes qualitatively, especially for low and intermediate values of λ, when high values of K are still quite likely, and low levels of IPR. Indeed, the effects (C) and (D) are driven by the closed mode which exists and dominates the open sales when K and L are high. This explains the inverted U-shaped relationship for sufficiently high λ. For sufficiently high λ, high knowledge levels are very unlikely, so the closed mode is irrelevant for all IPR protection levels above a certain threshold; investment coincides with that in the open mode, and therefore declines as IPR protection increases. When IPR protection is very low, the parties choose the closed mode for a broader range of K (i.e. $\widehat{K}(L)$ is lower). As IPR protection rises from very low levels, the close mode becomes infeasible at very low knowledge level, the mode switching effect (D) is very strong and the aggregate development expenditures increase. This effect is especially important for $\lambda \geq 7$ where the lower levels of knowledge are very likely.

4.2.2 IPR protection and development expenditures

In this subsection we study the effect of change in the enforcement of IPR holding the leakage from description constant.[17] We reproduce the simulations above for various $Lo \leq Lc$ holding L_c constant. The results are very similar. Again, for a large range of parameters we find the inverted-U-shaped relationship between IPR protection and development expenditures. This relationship cannot be explained by the open mode effects alone.

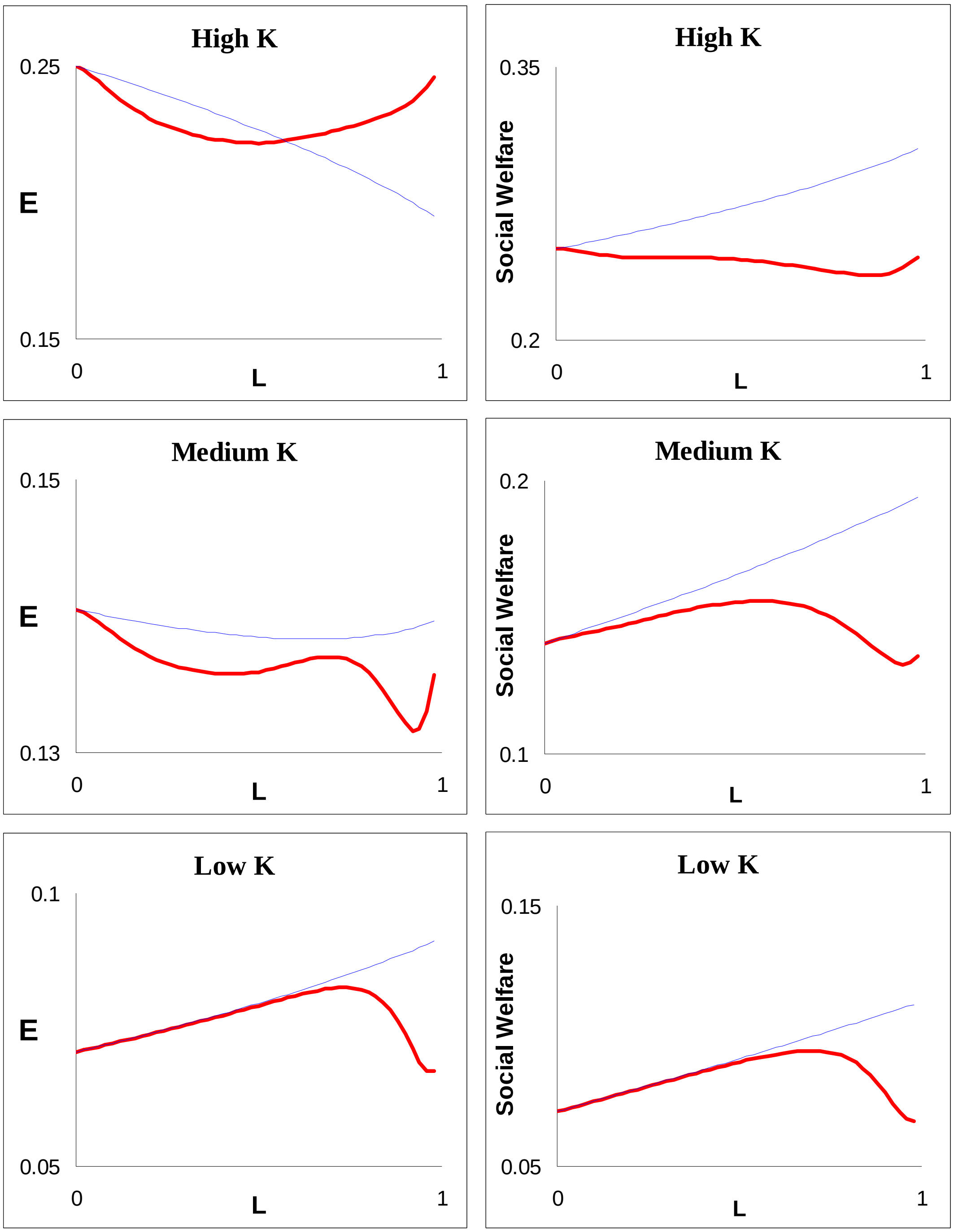

Figure 9: The aggregate development expenditures $E = E_1 + E_2$ and the welfare $1-(1-P_1)(1-P_2)-E$ as a function of leakage L in the case $L_o = L_c = L$. The bold line shows the relationship given the equilibrium (i.e. ex interim privately optimal) mode of disclosure. The thin line is the aggregate development expenditure in the open mode (as if the closed mode were ruled out exogenously). The three scenarios are “High K” ($\lambda = 0$, $\mathsf{E}K = 0.5$, $g(1)/g(0) = 1$), “Medium K” ($\lambda = 3$, $\mathsf{E}K = 0.28$, $g(1)/g(0) = 0.05$), and “Low K” ($\lambda = 7$, $\mathsf{E}K = 0.14$, $g(1)/g(0) = 0.0009$).

Figure 10 shows that the relationship between IPR protection $(1 - L_o)$ at $L_c = 0.9$ and the aggregate development expenditures for different values of λ is similar to the one in Figure 9 above. The results are robust to the choice of L_c. It turns out that the most important effect behind the inverted U-shape is the mode-switching effect (D): increased leakage in either open or closed results in a higher likelihood of the closed mode.

4.2.3 Summary

In both cases above, the total development expenditures and welfare can be higher with the closed mode when the latter is relatively efficient. This effect is important when higher levels of K are more likely as when $\lambda \in [0, 3]$ and IPR protection is low $L_o \geq 0.5$. Nevertheless, for $\lambda = 3$, an inverted-U-shaped relationship obtains over a large range of IPR protection. In contrast, for $\lambda = 0$, the closed mode effects dominate for higher levels of leakage, leading to a U-shaped relationship between IPR protection and total development expenditures.

To summarize, the shape of the relationship between $(E_1 + E_2)$ and L_o varies substantially with the ex ante distribution of knowledge K. While for high λ $(\lambda \geq 7)$ the relationship has an inverted-U shape, in the case of an uniform distribution $(\lambda = 0)$ the relationship is actually U-shaped. For intermediate values of parameters $(\lambda = 3)$ the graph is a superposition of an U-shape and an inverted-U-shape. Our numerical example is highly stylized, so it is hard to judge which values of parameters are realistic. Still, we may presume that the range $\lambda \in [3, 7]$ is somewhat consistent with observed characteristics of modern R&D (see Teece, 2000).

5 Related literature

Our paper is related to several strands of literature. First, we contribute to the literature on knowledge disclosure. The formal modelling of knowledge disclosure in the context of R&D began with two key papers, by Spence (1984) on exogenous knowledge spillovers across competing firms (DUs), and by Bhattacharya and Ritter (1983) on a RU cum DU voluntarily revealing part of its interim innovative knowledge to investors to raise finance for development towards a marketable invention, but enhancing the capabilities of competing DUs in the process. In two subsequent papers, Anton and Yao have extended their analysis to the context of knowledge licensing and patenting choices. In Anton and Yao (2002), a partial disclosure of the knowledge occurs in the context of closed sales of interim knowledge by an RU, which are backed up by her warranties for its non-performance in the development stage. Both patented and non-patented knowledge disclosures are considered in Anton and Yao (2004), with qualitative results related to those of our model.

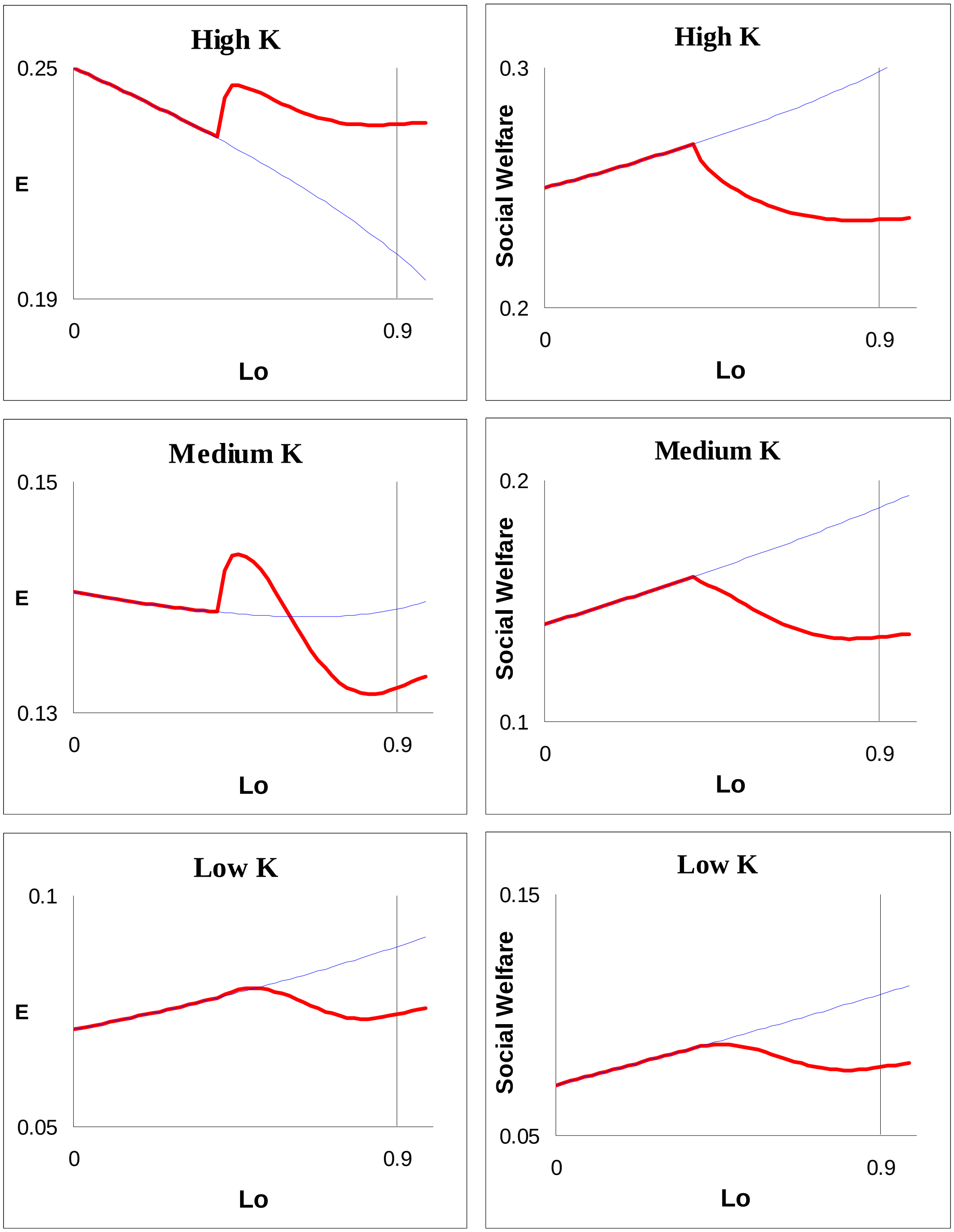

Figure 10: The aggregate development expenditures $E = E_1 + E_2$ and the welfare $1 - (1 - P_1)(1 - P_2) - E$ as a function of IPR protection L_o in the case $L_c = 0.9$. The bold line shows the relationship given the equilibrium (i.e. ex interim privately optimal) mode of disclosure. The thin line is the aggregate development expenditure in the open mode (as if the closed mode were ruled out exogenously). The three scenarios are “High K” ($\lambda = 0$), “Medium K” ($\lambda = 3$), and “Low K” ($\lambda = 7$).

The impact of revenue-contingent licensing fees on the DUs development efforts was modelled in Bhattacharya, Glazer and Sappington (BGS, 1992), which developed a theory of ex ante optimal licensing fee contracts – including those respecting interim wealth or verifiability constraints – for a research joint venture (RJV) across several RU cum DU firms. Related results on the breadth of patents, and its impact on the sharing of revenues and thus on research efforts in a multi-researcher cumulative R&D environment, were developed by Chang (1995) and by Green and Scotchmer (1995). Llobet, Hopenheyn and Mitchell (2000) have recently analyzed a compulsory licensing scheme for the transfer of patent rights to later sole inventors in a stationary Markovian environment. Denicolo and Franzoni (2004b) studied the effect of leakage and first-inventor defense on the decision to patent or to rely on secrets. See also Bhattacharya and Chiesa (1995) and Bessen and Maskin (2000) for models of endogenous knowledge spillover and research incentives across symmetric RU-cum-DU firm, without licensing *per se*.

The possibility of knowledge sale or licensing, even when disclosed knowledge cannot be verified by courts and its description causes full spillover to its receiver, was noted by Anton and Yao (1994). They modelled an RU incapable of development who proposes a closed sale of knowledge to a DU, and extracts a payment from him via the threat of revealing this knowledge to another competing DU also if such a payment is not made.[18] We extend their analysis by explicitly modelling RU's incentives in a setting where the spillover of knowledge from its description is only partial. We describe a structure of knowledge licensing fees that may rule out RU's making a clandestine sale to another DU, which would diminish the originally licensed DU's prospects of being the sole or first inventor. At the same time, we retain their assumption that the external financing needs of an RU who might try to develop her interim knowledge, are sufficiently great so as to generate grossly inadequate incentives for her development "effort" on non-contractible inputs, so that she is better off selling her knowledge exclusively to one of the two competing DUs.

BGS had assumed that the quality of any interim knowledge exchanged via a possibly non-exclusive license is verifiable in courts, following a final invention by a licensee. Subsequent papers on collaborative R&D – in which first-stage research and second-stage development may yield fruit via separate entities – has tried to relax this assumption to incorporate interim bargaining subject to constraints arising from ex ante property or control rights. These have built on the formalization of Incomplete Contracts and "hold-up" problems in the papers of Grossman and Hart (1986) and Hart and Moore (1990). An early application of this type of modelling to R&D was contained in Aghion and Tirole (1994), which analyzed knowledge licensing fees and their implications for incentives to expend non-contractible efforts or invest in research and development, by a RU incapable of development and a DU incapable of first-stage research. They reached conclusions similar to those of Hart and Moore (1990), regarding the optimal allocation of control rights to the RU versus the DU, under the (strong) assumption that under DU's control RU is induced to disclose all its knowledge for no incremental rewards, whereas an independent RU obtains the Rubinstein (1982) non-cooperatively bargained share of any revenues arising from the final invention if it occurs, which in turn diminishes the DU's ex interim development incentives.

Recent papers by Anand and Galetovich (2000), Dasgupta and Tao (1998), Tepperman (2000), and Rosenkranz and Schmitz (1999), have attempted to incorporate more key features specific to an R&D setting within this type of (Grossman-Hart-Moore) property rights-based framework. Rosenkranz and Schmitz (1999, 2002) consider collaborative R&D ventures in which each partner makes decisions regarding both her non-contractible effort as well as her knowledge disclosure to her partner(s). However, their key notion of a common asset – which its owner may deny the other partner access to as a bargaining threat – is quite abstract in an R&D context. Moreover, in the two levels of knowledge and outcomes setting of their model, the ex ante optimal "complete contracting" licensing fees of Bhattacharya, Glazer, and Sappington (1992) – those respecting interim zero-wealth constraints – could be implemented via the threat of competition by the licensor rather than exclusive production by the licensee in the event of ultimate inventions by both, which is analogous to the threat used to extract knowledge licensing fees in Anton and Yao (1994).[19]

Our work is also related to the paper by Bulow and Klemperer (1996) who show that a simple auction with $N+1$ bidders is usualy better for the seller, than an optimally structure negotiations with N potential buyers. While the basic logic is similar – the choice is between 1 buyer in closed mode and between auctioning to 2 buyers in the open mode – the setting of selling non-marketable knowledge in sequential R&D is quite different, in particular, in terms of presence of leakage and importance of DU's incentives to develop. Hence, it is not surprising that closed mode may emerge in equilibrium exactly when leakage is high and when providing the incentives is easier (that is when knowledge is more valuable).

6 Concluding remarks

We develop a model of two-stage cumulative research and development (R&D). Research Unit (RU) produces non-verifiable knowledge that has no market value per se but it can be used by Development Units (DUs) to create a marketable product. Due to the non-rivalrous nature of knowledge, there is a risk that after disclosing to one DU, RU will further disclose the information to a competing DU. We consider two alternative mechanisms that create RU's commitment to exclusive disclosure: the 'open sale' based on patenting the interim knowledge, and the 'closed sale' where precluding further sales requires the RU to obtain a share in the licensed DU's post-invention revenues.

An open or patented sale provides legal support for exclusive disclosure, but it also involves leakage of a certain portion of the knowledge to the public in the process of filing a patent application. A closed sale helps to reduce such leakage, but the need for giving away a share of post-invention revenues to RU weakens the licensee DU's incentives to invest in development. We explicitly model the extensive form bargaining in both modes of disclosure, and find that the parties are more likely to choose the closed mode if the interim knowledge is very valuable and intellectual property rights are not very well protected. We also generate potentially testable predictions in the structure of knowledge licensing fees in closed sales.

We do not obtain unambiguous welfare implications. Our model shows that there is no uniform ranking of the two knowledge disclosure modes even in terms of overall research effort induced. We find that both the comparisons of magnitude of research and development expenditures across the modes of knowledge disclosure, and the relationship between overall knowledge-development efforts and the strength of intellectual property rights protection, depend qualitatively on the ex ante distribution of interim knowledge levels.

Throughout our paper, we have deemphasized the incentives of first-stage Research Units to generate knowledge, and the impact of increased IPR protection thereon. In part that is because the qualitative impact of (potential) leakage on RU's payoffs can differ substantially depending on her chosen mode of knowledge sale. RU's payoff is decreasing in the leakage parameter in open sales, but possibly increasing in leakage in closed sales. Furthermore, even if increased IPR protection augments RU's interim payoffs, and enhances her incentives for creation of higher levels of interim knowledge, it is far from clear that such an effect would generate an inverted U-shaped relationship between overall R&D expenditures and the strength of IPR protection. As we have shown above, such a relationship may easily result from endogenous private choices over modes of licensing of different levels of interim knowledge.[20]

Notes

1. There could also be costs of disclosure to the capital markets, thereby augmenting the knowledge of competing developers, as in Bhattacharya and Ritter (1983).

2. As Gallini (2002) notes, based on the paper of Jensen and Thursby (2001), the impact of the Bayh-Dole Act of 1980 – which empowered universities to retain patent rights to their innovations developed with federal funds, and offer exclusive licenses for the commercial development thereof – on stimulating technology transfer to the for-profit sector is "compelling". Others have argued that interim knowledge transfers to multiple developers, via non-exclusive knowledge licenses or greater disclosure in patents for example, may do more to stimulate inventions. In our model, for a subset of interim knowledge levels overall developer surplus may indeed be enhanced by disclosing interim knowledge fully to both DUs, but we show that the RU's reduced bargaining power in such multiple licensing will lead her to prefer exclusive licenses. Teece (2000) concurs with this view, see also Bolton and Whinston (1993).

3. The researcher's share may be quite substantial. Recently, a Japanese court enhanced the reward of an inventor, holding a patent jointly with his ex-employer, from 20,000 to 20 billion yen (189 million dollars); see New York Times (2004). Stakes are even higher in biotech-pharmaceutical licensing: the Hoffmann-La Roche's recent deal with Antisoma included a lump-sum payment of $43 million plus 10-20 per cent of royalties on any products Roche brings to market. In theory, payments to Antisoma could exceed $500 million if all existing products were successfully launched (Featherstone and Renfrey, 2004). The choice of contracts on revenue rather than on net profit may be driven by concerns such as in Anand and Galetovic (2000), of the possibility of the buyer inflating his reported expenditures to hold up the seller of the knowledge.

4. After writing the first draft of this paper, we have also become aware of Lai et al. (2003), who deal with similar issues, albeit in a different framework. In particular, they exogenously parameterize the effect of opportunistic disclosure on RU's and DUs' ex post revenues, while we explicitly model a development race. Another related paper is Baccara and Razin (2002) where the original innovator has to share information with his collaborators who could potentially leak his knowledge to a different partner. The innovator appropriates a substantial part of the surplus, because he can threaten the collaborators with the loss of ex post monopoly rents via further disclosures. While our closed mode of knowledge sales is based on a similar idea, unlike Baccara and Razin we model our RU's stake in her licensee DU's ex post revenue as being contractible.

5. Such contracts would involve a seller paying a fine, e.g. forfeiting its licensing fee, if a non-licensee DU were to invent. However, courts may refuse to enforce such contracts as long as they believe that the other DU might have originated similar knowledge on his own. As Denicolo and Franzoni (2004a, p. 367) note: "Trade secret law does not protect the inventor from independent rediscovery" and that is exactly what the other DU – benefitting from a second sale by an RU – would claim.

6. An early theoretical argument for such a relationship between IPR protection in the form of patent length and the expected value of resulting inventions was provided by Horwitz and Lai (1996). Sakakibara and Brensetter (2001) have analyzed Japanese evidence on this issue, based on the impact of patent reforms.

7. We assume that the dependence of probability of invention on the outcome of research K and development effort E is similar to a two-factor production function with constant returns to scale. We use the simplest functional form for analytical tractability. Most our qualitative results hold for any neoclassical $p(K, E)$ with constant returns to scale.

8. In some cases, patenting may involve a greater extent of knowledge leakage than private sales. For example, the choice of Process rather than Product licensing in Indian patent law for pharmaceutical innovations, prior to her joining the WTO, probably facilitated the development of alternative processes for the same final product, by requiring patent applicants to disclose more fully the original processes for manufacturing their products. In contrast, closed licenses for manufacturing these products are likely to have resulted in similar levels of disclosure about innovators' processes only after agreement on royalties.

9. As well as other results, the fact that sP_c decreases in K is not an artefact of a specific functional form. Indeed, the incentive compatibility constraint requires that $s = s^*(K, L)$ satisfies $sP_cP_d = U_d(P_d) - U_d(\widetilde{P}_d)$, where U_d denotes the DU_j 's payoff gross of any payments to RU. In other words, $sP_c = \left[U_d(P_d) - U_d(\widetilde{P}_d)\right] / P_d$, so that sP_c declines with K whenever the RHS does, which is likely as long as $U_d(P_d)$ is weakly concave in K, and leakage is weakly convex in K.

10. In an unpublished appendix, we explore these issues in full detail studying arbitrary contracts contingent on 2x2=4 outcomes of discovery by each DU. It turns out that the results are very similar. Although more general contracts do reduce inefficiency due to the binding IC constraint, the equilibrium arrangements still involve a positive royalty stake $s > 0$ and have the same comparative statics properties.

11. If the open mode is suboptimal ($T_o < T_c$), then the outside option can bind for at most one party. The precise division of the surplus T_c in such a sale is unimportant for our qualitative results, however. For an analysis of buyer-seller bargaining under asymmetric information about the knowledge level K, see d'Aspremont et al. (2000).

12. E.g. in the Figure 8, the divide between the open and closed mode would shift upwards at most by 0.016. For most Ls, the divide would not change at all. In the working paper version Bhattacharya and Guriev (2004) we also explore the implications of RU's financial constraint for incentives to generate knowledge and for RU-DU vertical integration in an extension where the level of knowledge depends on RU's ex ante effort.

13. We have not been able to produce a simple analytical proof but the numerical calculations do show that it is the case for all L_c, L_o, K. We have also found that the situation where RU prefers open mode even if the joint surplus is higher in the closed mode does require L_o to be substantially below L_c and K being very close to $\widehat{K}(L_c)$. E.g. if $L_c = 0.9$, it only occurs for $L_o \leq 0.78$; if $L_c = 0.5$, it requires $L_o \leq 0.28$.

14. The full-blown analysis of this case should also taken into account a potential for a war of attrition between the two DUs. As both DUs benefit from switching to the open mode, each can wait for the other one to pay the RU for patenting.

15. We need to determine the sign of $E_o - E_c$ at $K = \widehat{K}(L)$, where $E_c = P_c^2/(2K) = K(1-s)^2/2$ is the development effort in the closed mode. The sign is positive whenever $\left[(1 - L\widehat{K}(L))^2 + L(1 - \widehat{K}(L))^2\right]/(1 - L\widehat{K}^2(L))^2 > (1 - (1 + L)/4)^2$. The latter inequality holds. The right-hand side is below 9/16 for all $L \in [0, 1]$, while the minimum value of the left-hand side is 0.83. Indeed, the left-hand side decreases in L for all $L < 0.52$ and then increases in L; at $L = 0.52$ the left-hand side equals 0.83.

16. Some scholars have claimed that reforms in US patenting law, and its improved implementation by a specialized appeals court, are responsible for a dramatic increase (doubling or more) in US patent registrations and small firm research expenditures over the 1990s (see Gallini, 2002). The study of Kortum and Lerner (1998) disagrees with this view. They find that patenting rates increased nearly as much in sectors outside those directly affected by "stronger" patent law, which recognized innovations such as novel software or genetically altered life forms for patents. They attribute the increase in patenting to enhanced emphasis on and funding for applied research, often leading to more numerous marginal contributions. In sectors such as biotechnology, this might have been spurred by major discoveries in earlier years.

17. Earlier, Scotchmer and Green (1990) developed a two-stage model of cumulative R&D, in which patenting (disclosure) of an interim innovation causes full leakage of its implications for second-stage inventions to other RU cum DUs. They analyzed endogenous choices of the timing of patenting under alternative IPR protection regimes.

18. Dasgupta and Tao (1998) and Tepperman (2000) consider optimal allocations of Property Rights to patented, and marketable, innovations when abilities to contribute to its further developments differ among its multiple originators. Anand and Galetovic (2000), in contrast, focus on optimal financing of first-stage research, and collaboration between initial research units with potentially efficiency-enhancing developers of their knowledge, despite the possibility of the latter "holding up" the former, by misstating their costs of development. Our ex post revenue-contingent RU royalties, unlike profit-sharing RU-DU contracts, do not give rise to these issues.

19. Another interesting avenue of research is to study the implications of our analysis for the choice of the first-stage research projects. Under different circumstances, RU may prefer projects with more/less valuable but also more/less portable knowledge (that is *endogenously* high/low K and L) involving different quantity and quality of employees and different structure of research units.

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