Knowledge Licensing, Patents, and Optimal Organization of Research and Development[1]

Sudipto Bhattacharya[2] and Sergei Guriev[3]

First draft: February 2004
Revised: November 2004

[1]Work on this research project was begun when Bhattacharya was a Visiting Professor at the New Economic School over May and June, 2003. We thank the NES as well as Arizona State and Princeton Universities, for their very congenial research environments and financial support that have spurred our progress. We gratefully acknowledge helpful comments from James Anton, Patrick Bolton, Andrei Bremsen, Vincenzo Denicolo, Oliver Hart, Eric Maskin, Jean Tirole and Luigi Zingales, without implicating them in any of the errors and omissions remaining in our paper. We also thank seminar participants at Bologna, GSB Chicago CORE, Gerzensee, Harvard-MIT, London School of Economics, New Economic School, Said Business School at Oxford, Institute for Advanced Study (Princeton), Santa Barbara, Toulouse for their comments. Patrick Kelly at ASU provided excellent research assistance.

[2]London School of Economics, and CEPR. E-mail: s.bhatt@lse.ac.uk
[3]New Economic School, Moscow, and CEPR. E-mail: sguriev@nes.ru

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 interim 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. We also develop a rationale for the ex ante acquisition of control rights over the RU by a DU, rooted in the RU's incentives to create knowledge under alternative modes of sale thereof, and her wealth constraint in ex interim bargaining.

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 innovative idea ("Knowledge"). The idea has no value to consumers but can 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 or 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 otherwise. We then characterize when each mechanism is more likely to be chosen, and derive the implications of these choices for the organizational form of R&D. In particular, we focus on the structure of the licensing fees (lump-sum vs. revenue-contingent royalties), and the impact of ex ante control rights acquired by the Development Units over Research Units, on their respective incentives to develop and to generate knowledge.

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 (Hensley, 2003, Morais, 2003). The restructuring paid off and other companies followed GSK, competing for both late- and early-stage licensing deals (Naik, 2002, 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 or in revenue-contingent royalties, or through participation in joint ventures. 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).

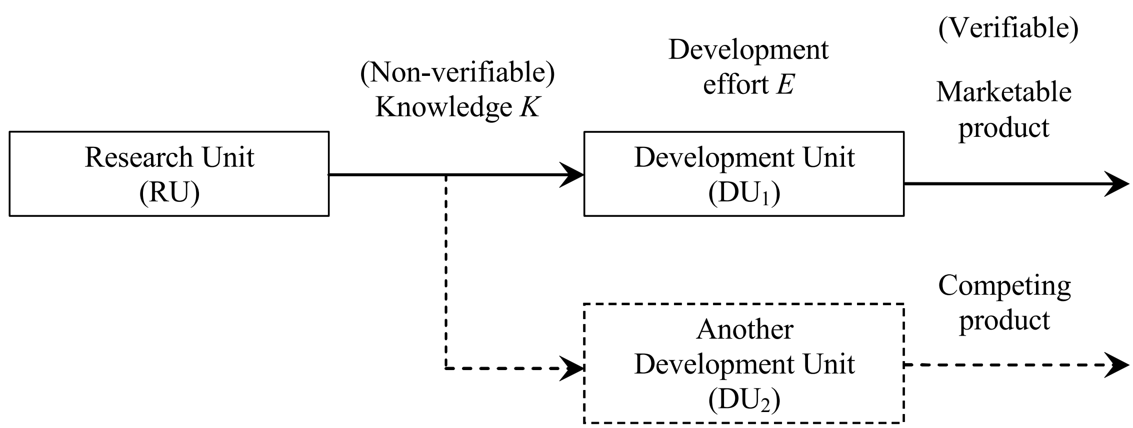

Figure 1: A model of sequential research and development, and knowledge licensing.

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.

Several issues concerning the licensing of such intellectual property are of a great 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 payments and royalty fees in providing incentives for research and development? What are the implications of Development Units financing Research Units in exchange for some degree of control over their subsequent actions, such as the right of first offer for licensing their inventions?

We attempt to answer these questions within an incomplete contract setup where two potential buyers of non-verifiable knowledge compete to obtain the license to develop the knowledge (Figure 1). Unlike conventional incomplete contract models, we take into not only the fact that the value of 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 weakens 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 an exclusive license.

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".[1] 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.

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 "tacit" (Teece, 2000) or non-codifiable knowledge. Such knowledge is hard to protect using IPR law, since description of its features leads to prospects of innovating around the patent, causing a partial spillover of capabilities for second-stage invention on the basis of description from the publicly available patent. 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 of innovations involved in the patenting process.

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).[2] If this revenue share is sufficiently high, the seller will 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.[3]

The buyer's incentive to invest in development are undermined if it has to give away a very 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 makes patenting a less attractive option. On the other hand, in private sales, leakage may even help 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 is less obvious, and follows from the analysis of incentives in a royalty contract.

The higher the value of the knowledge, the easier it is to provide the knowledge seller with incentives for not disclosing to the buyer's competitors. Indeed, if the expected revenues are higher, a smaller royalty share in the buyer's revenues will be sufficient to make sure that the seller would not wish to dissipate the monopoly rent of her buyer. And the lower the royalty share, the less distorted is the buyer's incentive to invest in development. On the other hand, in the public mode of disclosure, a higher level of leaked knowledge may incentivise competing developing units, reducing returns to the licensee's effort. We endogenise the impact of greater leakage of knowledge via patenting on development efforts as a Nash equilibrium in an asymmetric contest for the rents arising from final invention.

The recent paper of Anton and Yao (2004) also contains results similar 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 sole purpose of partial knowhow 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 penalties are taken to be independent of the quality of disclosed knowledge. In contrast, 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 develop our analysis in two directions. First, 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.[4] 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 emerges naturally, as the strength of IPR has quite dramatically different impacts on levels of development expenditures in patented vs. non-patented modes of knowledge licensing.[5]

We also develop a rationale for the ex ante acquisition of control rights over the researcher by the knowledge buyer, rooted in the researcher's incentives to create knowledge under alternative modes of sale thereof, and her wealth constraint in ex interim bargaining. We make a clear distinction between physical and intellectual capital. In doing so we invoke the principle of inalienability of human capital, as in Hart (1995), to intellectual property, maintaining the assumption that whether she is independent or vertically integrated (via Corporate Venturing for example), the researcher always retains the option of patenting her knowledge for licensing. In our formulation of vertical integration, control rights are defined as the development unit's right to veto coalitions of the researcher with third parties. This definition of control rights leads to a non-trivial tradeoff between the costs and benefits of corporate venturing. If the researcher cedes control rights ex ante, she may essentially lose ex interim flexibility in choosing a more profitable mode of knowledge licensing. However, we show that even if corporate venturing leads to inefficient ex interim outcomes, it may improve ex ante incentives to invest in the production of higher levels of knowledge.

The rest of the paper is organized as follows. In Section 2, we set up our model, describing its timing and notation. In Section 3 we characterize the equilibrium contract and mode of disclosure. In Section 4 we study comparative statics with regard to the degree of protection of intellectual property rights. In Section 5 we consider the role of RU's interim financial constraints, and provide a rationale for corporate venturing by a DU. Section 6 discusses related literature. Section 7 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. We assume, until Section 5, that RU is not controlled by either DU.

These parties undertake research (by RU) and development (by DUs) to create a new product. The investments in research and development are sequential. First, research is undertaken in order to produce 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. The interim knowledge $K \in [0, 1]$ depends on the RU's non-contractible effort choice e. The c.d.f. of knowledge $G(K; e)$ is decreasing in effort e.

For each DU, his probability P of successful development is a function of his acquired knowledge and subsequent non-contractible development effort $E \in [0, 1/2]$:[6]

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

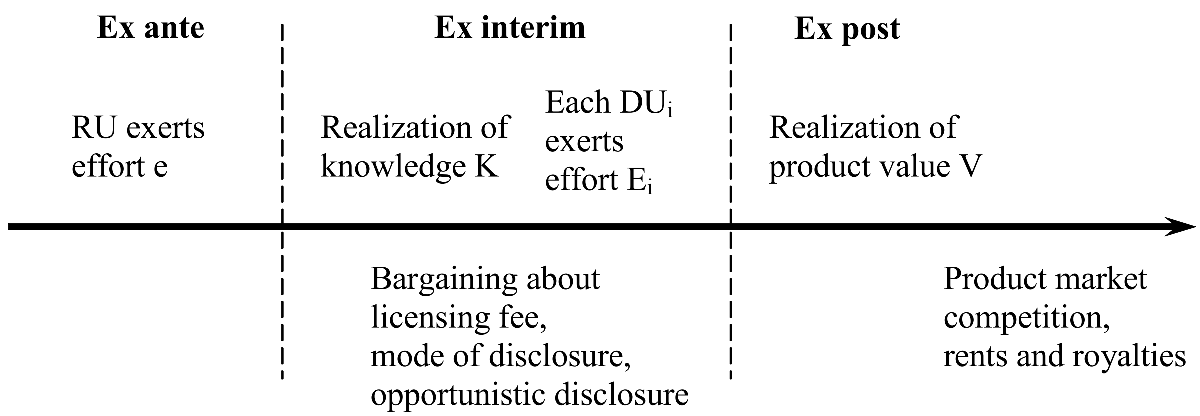

Figure 2: Timing.

Both research and development efforts e and E are measured in terms of their costs. 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

The timing of events is presented in the Figure 2.

Ex ante. RU undertakes effort e.

Ex interim. The parties, RU and the DU(s) to whom RU offers a license, observe the level of knowledge K; DUs do so based on its description by the RU. The parties then bargain about the choice of the mode of the full disclosure of the knowledge and about the licensing fee. Their bargaining proceeds as an alternating offer game. The two alternative modes of knowledge disclosure are as follows:

In the *open mode,* a patent (IPR) is registered, so that RU can commit to sell her knowledge to one party only.[7] This requires describing RU's knowledge publicly which involves a partial leakage of her knowledge; a proportion $L \in [0, 1]$ of the knowledge K is disclosed to both DUs. The firm i that buys knowledge chooses development effort E_i; the respective probability of development is $P_i = P_o = p(K, E_i)$. The other firm j chooses effort E_j, his probability of development is $P_j = \widetilde{P}_o = p(LK, E_j)$. The effort levels form Nash equilibrium strategies in the game between the two DUs.

In the *closed mode*, disclosure occurs through a private sale to one of the DUs (randomly chosen by an independent RU). The parties bargain about a contract contingent 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 from DU_i to RU and RU's share s (e.g. via royalties) in DU_i's ex post revenues.

After RU and DU_i agree on the terms of disclosure, DU_i chooses his development effort E_i. We denote P_c as his corresponding probability of invention. RU could also disclose her knowledge to DU_j subsequently. In this opportunistic deviation by RU, she would first describe her knowledge causing leakage LK (for symmetry's sake) to DU_j. 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 disagreed on the licensing fee, DU_j would develop on the basis of leaked information; in this case we denote his choice of probability of invention as $\widetilde{P}_d$. By choosing s appropriately, DU_i will try to preclude such 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.

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

2.3 Notation and assumptions

We assume that courts can verify ex post revenues (i.e. whether $V = 1$ or $V = 0$), but not the level of interim knowledge K, or the "effort" expenditures e and $E_{i,j}$. Observability of knowledge K is related to its description. Once RU describes knowledge to DU(s), the latter infer the level of knowledge K produced in the research stage. The full *content* of RU's knowledge is not thereby observed by either DU; this requires further disclosure. However, the description results in a leakage LK of 'enabling' (Anton and Yao, 2004) knowledge.

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. RU makes an offer to DU_i. DU_i either accepts the offer or makes a counter-offer. If RU rejects the counter-offer, she makes an offer to DU_j and so on. $\mathrm{DU}_{1,2}$ then choose their post-licensing levels of development effort (equivalently, their probabilities of successful development). We assume equal bargaining power in bilateral bargaining between a DU and an RU.

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. Similarly, F_c and F_o are the full licensing fees that this DU_i pays RU in these modes. We will denote as $U_{oi}(P_i, P_j; K)$ the expected ex interim payoff of this DU in the development race, whereas the other DU$_j$ chooses probability of invention P_j to maximize $U_{oj}(P_j, P_i; LK)$. According to (1), DU$_i$'s effort cost is $E_i = P_i^2/(2K)$ 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 LK; he maximizes his payoff

$$U_{oj} = [(1 - P_i)P_j - P_j^2/(2LK)] \tag{3}$$

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

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

$$U_c = [(1 - s)P_i - P_i^2/(2K) - \{F_c - sP_c\}] \tag{4}$$

where P_c is the optimal choice of P_i in this mode. The RU's payoff F_c consists of the royalty sP_c and the cash payment $\{F_c - sP_c\}$ 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 chose via bilateral bargaining between RU and DU$_i$; the contract terms incentivise RU not to sell her knowledge do DU$_j$ later.

It is important that registering IPR is an outside option for both RU and the DU that is offered a closed knowledge sale. The RU has this option by definition. On the other hand, DU$_i$ may also force RU to register the patent by making non-serious offers after RU has described her knowledge. Certainly, RU may choose to switch to negotiating with DU$_j$. However, the latter strategy will not increase RU's payoff relative to an open sale, since RU has described knowledge during the prior negotiations; DU$_i$ has already obtained LK.

3 Choosing between alternative modes of disclosure

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, $T_o(K, L)$ and $T_c(K, L)$, 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 (for 'open') and obtains knowledge K. At the same time, knowledge LK 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 LK, and will therefore receive $[(1-P_o)\widetilde{P}_o - \widetilde{P}_o^2/(2LK)]$. Here the probabilities $\left\{P_o, \widetilde{P}_o\right\}$ satisfy the Nash equilibrium conditions:

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

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

$$P_o = \frac{K - LK^2}{1 - LK^2}; \quad \widetilde{P}_o = \frac{LK - LK^2}{1 - LK^2}. \tag{5}$$

Note that P_o is increasing in K for all L, 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 $L < 1$. 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 alternating 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* $U_o \triangleq U_{oj}\left(\widetilde{P}_o, P_o; LK\right) = \left[(1-P_o)\widetilde{P}_o - \widetilde{P}_o^2/(2LK)\right]$, *while RU obtains* $F_o = [\{P_o(1-\widetilde{P}_o) - P_o^2/(2K)\} - \left\{(1-P_o)\widetilde{P}_o - \widetilde{P}_o^2/(2LK)\right\}]$ *from DU_i.*

Proof. The unique subgame perfect equilibrium 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 RU will not agree to a counter-offer that reduces her payoff, since 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. ■

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 binding. 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 (5) we obtain the equilibrium payoffs of the RU and DU:

$$T_o = \frac{K(1-LK)^2}{2\left(1-LK^2\right)^2}; \quad F_o = \frac{K(1-L)}{2\left(1-LK^2\right)}; \; U_o = T_o - F_o = \frac{K(1-K)^2 L}{2\left(1-LK^2\right)^2}. \tag{6}$$

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

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:

$$[sP_c - sP_c(1-P_d)] \geq \left[\left\{(1-P_c)P_d - P_d^2/(2K)\right\} - \left\{(1-P_c)\widetilde{P}_d - \widetilde{P}_d^2/(2LK)\right\}\right] . \tag{7}$$

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, as noted in Section 3.2. P_d is chosen by DU_j if she has full knowledge, and $\widetilde{P}_d$ is her choice with leaked knowledge LK. For simplicity's sake we assume leakage L to be the same as in the open mode. This assumption is not important for our results; we discuss it later.

For a given share s, the left-hand side in (7) 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 LK, RU can obtain from DU_j at most the expression in the right-hand side. 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 (7).

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 :

$$P_d = \arg\max_p \left[(1-P_c)p - p^2/(2K)\right] = K(1-P_c); \tag{8}$$

$$\widetilde{P}_d = \arg\max_q \left[(1-P_c)q - q^2/(2LK)\right] = LK(1-P_c); \tag{9}$$

$$P_c = \arg\max_p \left[(1-s)p - p^2/(2K)\right] = K(1-s). \tag{10}$$

In equilibrium, RU and DU_i will choose the minimum possible $s \in [0,1]$ that satisfies (7). Cancelling the sP_c terms on in the left hand side of (7) and using (8) and (9), we rewrite the incentive constraint as

$$sP_cP_d \geq \left[K(1-P_c)^2/2 - LK(1-P_c)^2/2\right]. \tag{11}$$

By substituting (8) and (10) into (11), we obtain

$$sK(1-s) \geq (1-K(1-s))(1-L)/2; \tag{12}$$

or, for all $K > 0$

$$2s^2 - (1+L)s + (1-L)(1/K-1)] \leq 0 \tag{13}$$

Since the parties are interested in finding the lowest s that still satisfies (7), we need to solve for the smaller root of the quadratic equation obtained by setting (13) to equality.

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 $s = s^*(K;L)$ in her licensee DU's post-invention revenues, where $s^*(K;L)$ satisfies:*

$$s^*(K;L) = \left(1 + L - \sqrt{(1+L)^2 - 8(1-L)(1/K-1)}\right)/4 < 1/2. \tag{14}$$

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

$$\widehat{K}(L) = \left(1 + \frac{(1+L)^2}{8(1-L)}\right)^{-1}. \tag{15}$$

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 $K < \widehat{K}(L)$ 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, $K < \widehat{K}(L)$, RU's returns to opportunistic disclosure (the right-hand side in (7)) increase in s so rapidly that the benefits of keeping DU_i a monopoly (the left-hand side in (7)) never catch up with it. Since $P_c = K(1-s)$, sP_c reaches its maximum at $s = 1/2$, implying $s^*(K;L) \leq 1/2$.

Whenever the closed mode is incentive-feasible, the RU's share $s^*(K;L)$ 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. Clearly, whenever $s = s^*(K;L)$ exists, $s = s^*(K;L)$ decreases in K, and so that right-hand side of (12) 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

$$T_c = P_c - P_c^2/(2K) = K\left(1 - s^*(K;L)^2\right)/2 \tag{16}$$

is increasing in K. This joint surplus is concave in K and approaches $K/2$ as K increases; although $s^*(K;L)$ decreases in K, its rate of decrease slows down at higher levels of K.

The closed mode is sustainable when leakage L is high, since RU's payoff from a deviant second sale declines when L increases. Indeed, $\widehat{K}(L)$ decreases in L from $\widehat{K}(0) = 8/9$ to $\widehat{K}(1) = 0$. Also, the higher the leakage, the more efficient the closed mode. If L 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 $T_c(K,L)$ when L rises, since the share $s^*(K;L)$ fall in equation (16).

Unlike in the open mode where the joint surplus of RU and the licensed DU_i decreases in leakage L, joint surplus T_c in the closed mode *increases* with L.

3.3 Ex interim optimal mode of disclosure

The parties choose the mode that maximizes the ex interim joint surplus of RU and her licensee DU; we ignore RU's financial constraints until Section 5. In this subsection, we show that the closed mode dominates the open mode if L and K are sufficiently high. In the next subsection we solve for the bargaining outcome in the closed mode when it is chosen.

If the leakage L is low, the open mode dominates the closed mode. Indeed, if L is close to zero then 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 the risk of opportunistic disclosure in the closed mode is high, so DU_i has to give RU a very high revenue share; hence his probability of successful development is lowered. As IPR protection decreases and L rises, open sales become less efficient, while closed sales produce a higher surplus to RU and licensee DU_i.

In order to see why the closed mode is more efficient for high K, let us consider the case where K is sufficiently close to 1. If $K \to 1$, then (6) and (16) imply $T_c \to [\frac{1}{2}K - (1 - K)^2 \frac{K}{2}\left(\frac{1-L}{1+L}\right)^2]$; $T_o \to [\frac{1}{2}K - (1 - K)\frac{L}{1-L}]$. Therefore for any $L > 0$, 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 quite low, $K < \widehat{K}(L)$, then a private sale to one DU is infeasible ($s^*(K; L)$ does not exist), so the open mode is chosen.

The surpluses in the closed and the open modes $T_c(K)$ and $T_o(K)$ are always equal to each other at $K = 1$. For any given $L > 0$ the functions $T_c(K)$ and $T_o(K)$ may cross at most once more, at $K = K^*(L) < 1$. At this crossing point, $T_c(K)$ grows faster than $T_o(K)$. This result becomes clear once we consider the ratios of joint surplus T and the "ideal" joint surplus $K/2$ in each mode (Figure 3, right). 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 at increasing rate as the square of royalty share s^* declines (see (16)). 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. Hence in the open mode, $T/(K/2)$ is convex, while in the closed mode it is concave; they intersect at most once for $K \in (0, 1)$.

Thus, for a different levels of leakage L, the comparison of $T_c(K)$ and $T_o(K)$ satisfies one three cases (Figure 3). *First*, there is a case where the closed mode is more efficient whenever $s^*(K)$ exists: $T_c \geq T_o$ for all $K \geq \widehat{K}(L)$. This case holds for $L \in [0.25, 0.91]$. In the *second* case the structure is different: at K being $\widehat{K}(L)$ or somewhat higher, the open mode dominates. This case occurs when L is very low $L \in (0, 0.25)$ or L is very high $L > 0.91$. 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. As K increases above $\widehat{K}(L)$, T_c grows faster than T_o, and eventually overtakes it at some point $K^*(L) \in (\widehat{K}(L), 1)$. 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 $L = 0$. In this case, the open mode is always optimal: $T_o = K/2 > T_c$ for all $K < 1$.

All the three cases can be summarized as follows:

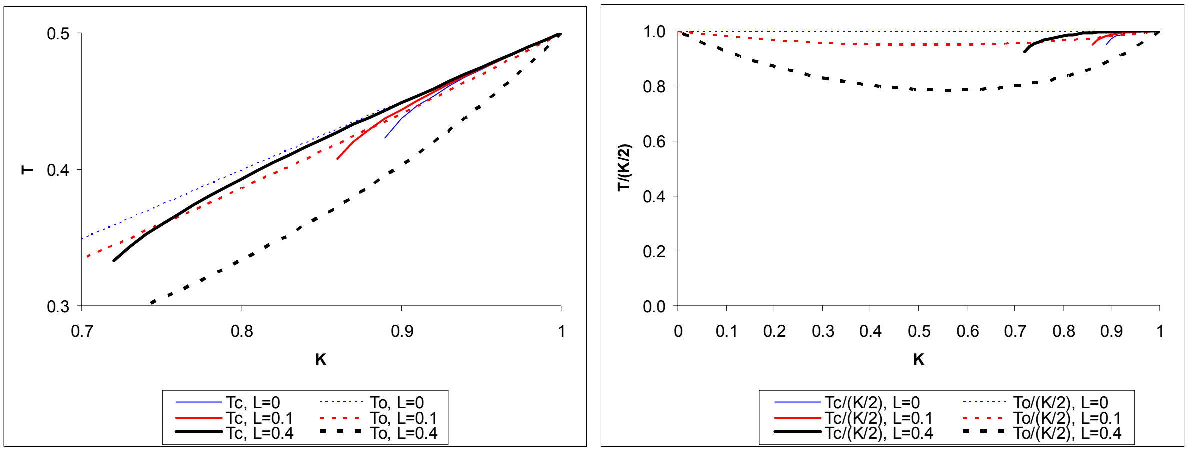

Figure 3: The left graph presents joint surplus as a function of K under open (T_o, dotted line) and closed (T_c, solid line) modes, for $L = 0.4$ (thick black lines), $L = 0.1$ (medium, red), and $L = 0$ (thin, blue). The right graph depicts joint surplus as a share of surplus without leakage $K/2$. 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.

Proposition 1 *If the closed mode of knowledge sale is more efficient for some $\widetilde{K}$, then it is also more efficient for all $K \geq \widetilde{K}$. Denoting K^* as the minimum level of knowledge for which the closed mode dominates the open mode, we have that: $T_c \geq T_o$ for all $K \geq K^*$, while if $K < K^*$ the closed mode either does not exist, or is dominated by the open mode $T_c < T_o$. As discussed above, such K^* exists with $K^*(L) \geq \widehat{K}(L)$, and the inequality binds for $L \in [0.25, 0.91]$.*

Figure 4 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.

3.4 Bargaining and surplus division

Once the research stage is complete, RU and the licensee DU$_i$ bargain over the disclosure fee in their chosen mode. As argued above, each party holds an outside option of switching to the open mode of knowledge sale. Once the IPR is registered, in the form of a patent, the two parties cannot return to private sales.

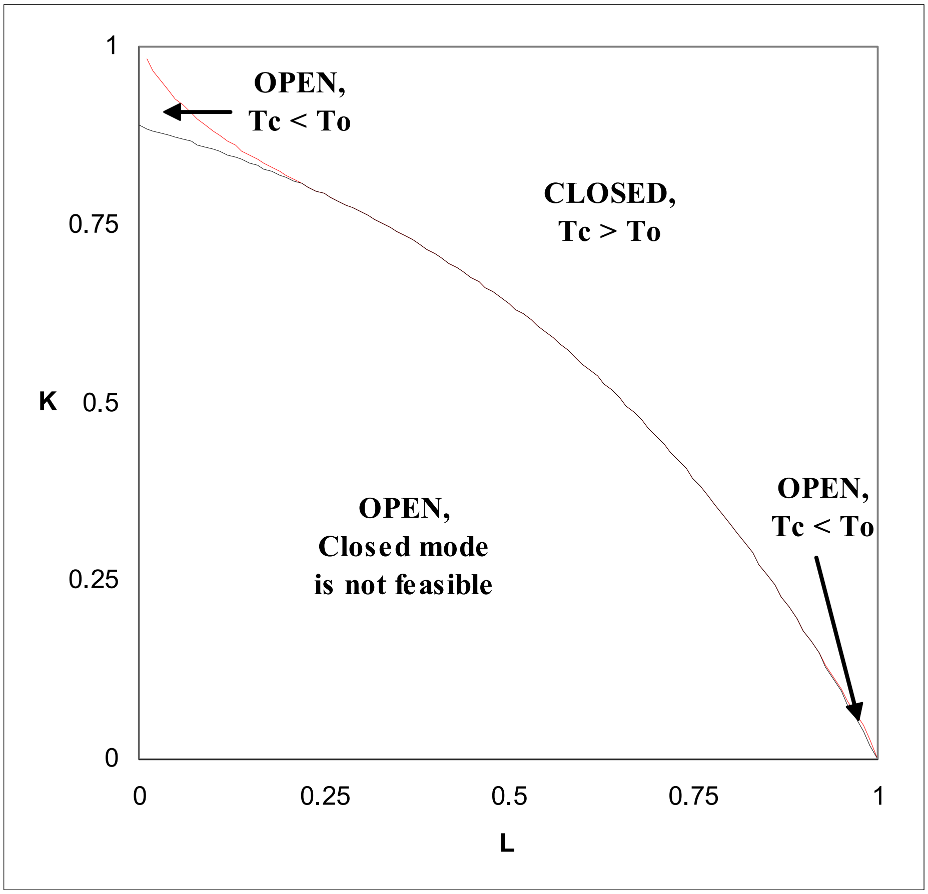

Figure 4: The optimal mode of licensing as a function of K and L. The (K, L) space is partitioned by two curves $\widehat{K}(L)$ (lower line) and $K^*(L)$ (upper line). For a given L, $\widehat{K}$ is the minimum level of knowledge for which the closed mode exists, K^* is the minimum level at which the closed mode dominates the open mode. The two curves coincide for all $L \in [0.25, 0.91]$.

The bargaining in the closed mode is a conventional alternating offer game (as in Rubinstein, 1982) where each party has an outside option with payoffs $\{F_o,\ T_o - F_o\}$ to RU and DU_i, respectively.

Lemma 3 *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.[8]

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.

The solution above neglects the RU's ex interim financial constraint. We assume that RU's payoff F_c consists of a stake in DU_i's revenues worth sP_c, and a lumpsum transfer $F_c - sP_c$. If RU is financially constrained, then one needs to take into account the fact that this transfer cannot be negative, $F_c - sP_c \geq 0$. In this Section we assume that since RU is independent, she could sign a contract with an outside venture financier that can relax her financial constraint. We discuss this financing arrangement in more detail in Section 5.

4 IPR protection and aggregate development effort

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 $1 - L$ and aggregate level of development investment by $E_1 + E_2$. 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 do not elaborate on the impact of IPR on social welfare; this would depend on specific assumptions about consumer surplus. Also, unlike development expenditures, full social returns to R&D are hard to measure 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, the total development effort by DU_1 and DU_2 in the open mode is

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

Lemma 4 *In the symmetric Cobb-Douglas case, total development effort in the open (patent-based) mode of knowledge sales E_o, either monotonically* decreases *with IPR protection $1-L$ (for $K \leq 1/3$) or has a U shape (if $K > 1/3$) with the minimum point of the U-shape $L = (3K-1)K^{-2}(3-K)^{-1}$ shifting from $L = 0$ to $L = 1$ as K increases from $1/3$ to 1.*[9]

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 ($L = 0$) 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 LK 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, 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 IPR protection $(1-L)$ increases for all K for which $s^*(K;L)$ exists.

There is yet another effect of IPR protection on the aggregate level of investment in development. If L becomes sufficiently high, parties switch from open to closed mode which at the margin results in lower effort. Indeed, consider the case of $L < 0.25$ 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 $K = \widehat{K}(L)$.[10] To summarize, we have:

Proposition 2 *There are four effects of stronger IPR protection on the total effort by DUs: (A) effect on the licensee's effort in the open mode (positive); (B) effect on the non-licensee's effort in the open mode (negative); (C) effect on the DU's effort in the closed mode (negative); (D) effect of switching from closed to open mode (positive). The latter two effects are associated with the closed mode and are therefore relatively more important for higher knowledge levels K, and for lower levels of IPR protection $(1-L)$.*

As shown above in Lemma 4, in the open mode total non-contractible development expenditures as a function of $(1-L)$ may be monotonic or U-shaped but it never has 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, closed mode effects are more important, hence investment start to decline (due to (D)).

We illustrate in Appendix B below numerical examples in which introduction of the closed mode can indeed produce an inverted U-shape relationship between IPR strength and aggregate development expenditures. In these examples, we consider a family of truncated negative exponential distributions $G(K)$ of knowledge levels. These numerical examples also show that, when the probability attached to higher level of K is not too low, overall development expenditures can be higher when the closed mode is feasible, owing to the importance of the beneficial effect of leakage on surplus in the closed mode (C).

5 Control rights and ex ante incentives

In this Section we study the role of RU's ex interim financial constraints, and possible ex ante assignment of control rights over her to one of the two DUs. As argued above, RU's financial constraint may become binding ex interim, when her incentive compatible equity stake sP_c is sufficiently high. This results in potential ex interim inefficiency: there may arise a situation where the joint surplus is higher in the closed mode $T_c > T_o$ but the licensee DU$_i$ prefers the open mode. This disagreement occurs whenever $(T_o - F_o) > (T_c - sP_c)$. If RU had deep pockets, she would pay DU$_i$ at the interim stage for forgoing the open mode option, but since RU is cash constrained the ex interim efficient mode can only be implemented if she has some external source of financing.

First, we consider a situation where the parties ex ante agree on RU remaining independent. In this case the RU may overcome this ex interim inefficiency using outside venture capital. The second scenario is corporate venturing where RU can commit ex ante to remain financially constrained ex interim through giving control rights to DU_i.

If RU is independent and requires external financing ex interim, she may join forces with a venture capitalist (VC) who will pay $I = [(T_o - F_o) - (T_c - sP_c)]$ to DU_i ex interim in exchange of I/P_c shares out of the s shares of revenue accruing to its coalition with the RU.[11] It is crucial that such a VC is able to make sure that RU acts in the interest of the RU-VC coalition and does not disseminate knowledge to DU_j even though she only has a stake of $s - I/P_c$ in DU_i revenues. We believe that this is a reasonable assumption: VC is not a regular financial intermediary, but a specialized entity with reputational concerns, which can prevent opportunistic behavior by its coalition partner RU.

The second scenario is corporate venturing. Ex ante, RU and DU_i agree that RU will cede control rights to DU_i. We do not assume alienability of human capital nor memory erasing technologies. The transfer of control rights implies only that RU's outside financing can be vetoed by DU_i. Also, RU is required to start negotiations with DU_i first and is not allowed to sell to a competing DU_j exclusively in a closed sale with a share in DU_j's revenues (in the closed mode, the disclosure of knowledge to DU_j cannot be tracked but any revenue sharing contract is by definition verifiable). It is easy to see that under corporate venturing, DU_i could credibly veto a RU-VC alliance. One way to commit to this veto is to sign a contract ex ante that if RU signs any share contracts with outsiders, her partner VC must pay DU_i a sufficiently high penalty for a breach of her ex ante agreement with DU_i. We also assume that RU cannot make binding promises to the DU_i before forming a coalition with a VC.[12]

As corporate venturing rules out relaxing RU's financial constraint, it may result in knowledge licensing via the open mode when the closed mode is ex interim efficient. Why would parties want to sign such a contract? The reason is that although the independent RU scenario is efficient ex interim, it may provide perverse incentives ex ante. As shown above, unlike F_o or $T_c/2$ the value of RU's revenue share sP_c is *decreasing* in K. Therefore the RU's financial constraint $F_c \geq sP_c$ tends to bind at low levels of K. By forcing open mode sales via corporate venturing for such knowledge levels, DU_i may indeed create ex interim inefficiencies. However, he may also improve RU's ex ante incentives to invest costly effort in research which is more likely to produce higher levels of K.

Whether corporate venturing is efficient ex ante depends on the relative strength of these ex ante and ex interim effects. Let us consider a simple example where RU can choose one of two effort levels: high or low. The high level of effort costs e dollars more,

	$K = K^L$	$K = K^H$
K	0.33	0.5
L	0.8	0.8
T_o	0.108	0.141
T_c	0.140	0.246
F_o	0.037	0.063
$T_o - F_o$	0.071	0.078
$T_c/2$	0.070	0.123
s	0.4	0.130
sP_c	0.08	0.056
$T_c - sP_c$	0.06	0.189
I	0.011	–
$sP_c - I$	0.069	–

Table 1: A numerical example where corporate venturing is ex ante efficient

but also produces higher knowledge $K = K^H$ ex interim with probability 1. The low effort produces only $K = K^L$ with probability 1, where $K^L < K^H$.

Suppose that in both states the closed mode dominates the open mode: $T_c^k > T_o^k$, $k = L, H$; in the high state RU's financial constraint is not binding, while in the low state $s^L P_c^L > \max\{T_c^L/2, T_c^L - T_o^L + F_o^L\}$. The latter implies $s^L P_c^L > F_o^L$ so the RU's financial constraint is binding in the low state. Then corporate venturing matters in the low state, and will affect the RU's payoff if a lower level of effort is chosen ex ante.

Proposition 3 *Corporate venturing will strictly increase RU's research effort if*

$$\max\{T_c^H/2, F_o^H\} - e < s^L P_c^L - I^L \text{ and}$$
$$\max\{T_c^H/2, F_o^H\} - e > F_o^L. \quad (17)$$

Corporate venturing will be adopted ex ante if the change in research effort is cost-efficient:

$$(T_c^H - e) - T_c^L > 0. \quad (18)$$

Since the closed mode is more efficient in the low state, $s^L P_c^L - I^L = F_o^L + T_c^L - T_o^L > F_o^L$, the conditions (17) are consistent for some effort costs e.

Table 1 describes a numerical example where the conditions above are satisfied for a range of e. We consider the case with $L = 0.8$, $K^L = 1/3$, and $K^H = 1/2$. Indeed, the conditions (17) and (18) imply $e > 0.123 - 0.069 = 0.054$, $e < 0.123 - 0.037 = 0.086$, and $e < 0.246 - 0.14 = 0.106$. Hence, for all $e \in (0.054, 0.086)$ corporate venturing strictly increases ex ante welfare and will therefore be an equilibrium outcome.

Notice that in this example, for $K = K^L$, DU's payoff in the open mode $U_o = T_o - F_o = 0.071$ binds as an outside option relative to her symmetric share of the surplus in the close mode $T_c/2 = 0.070$. Thus, DU would not expect to be made an offer of a payoff greater than 0.071 if she were to allow the RU to form a coalition with VC ex interim.

In this example, corporate venturing allows DU_i to commit to force the choice of the open mode when K is low and RU's financial constraint is binding $sP_c > \max\{F_o, T_c/2\}$. Since corporate venturing makes the commitment credible, RU expects to suffer from the open mode, and therefore prefers to choose a higher level of effort whereby her financial constraint does not bind. Once the high effort level is taken ex ante, corporate venturing actually becomes irrelevant ex interim (financial constraint is not binding in the high state); hence corporate venturing does not even result in ex interim inefficiency. The latter is an artefact of the assumption that high effort level rules out the low state with probability 1. If the low knowledge state occurred under high effort with a positive but lower probability, the results in Proposition 3 could be easily generalized; but corporate venturing would now create a non-trivial probability of ex interim inefficiency.

6 Related literature

Our paper is related to several strands of literature. First, we contribute to the literature of 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 its competing DUs in the process.

The possibility of knowledge sale or licensing, even when disclosed knowledge can not 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.[13] 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.[14]

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 (2004) studied the effect of leakage and first-inventor devense on the decision to patent or to rely on secrets.

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), who built on and extended insights in the works of Klein, Crawford, and Alchian (1978) and of Williamson (1971, 1976). 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 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 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).[15]The paper by Fulghieri and Sevilir (2003) is most related to ours: the authors study how the optimal structure (integration vs corporate venturing) depends on importance of researc and on competition in the product market. They consider the competition between two RU-DU pairs and do not allow for opportunistic disclosure from RU to a different DU.

In our work, we follow Hart (1995) who assumes absolute inalienability of human capital.[16]The latter should surely extend to knowledge embedded in persons in a research unit, which they may well threaten not to disclose as part of a process of bargaining with potential developers thereof. Our formulation of DU's control rights over RU is thus closely related to Hart and Moore (2004), in which ex ante contracts rule out a subset of ex interim negotiations in order to improve ex ante incentives.

Our paper also contributes to the incomplete contracts and moral hazard in teams literature. On one hand, as in Aghion and Tirole (1994) and Lester and Talley (2000), there is a moral hazard in teams problem that may result in underinvestment by RU and/or DU. In our model, where R&D is sequential, this problem might have been tackled through buyout options (e.g. Noldeke and Schmidt, 1998). We show that the non-rivalrous nature of knowledge implies yet another dimension of moral hazard. Not only is there a risk of underinvestment by both the buyer and the seller, there is also a risk of opportunistic disclosure by the seller to the buyer's competitor. While this problem may be solved by the buyer providing a royalty stake to the seller, another moral-hazard-in-teams problem emerges – the greater share is given to the seller, the less the buyer's incentives to invest. This may explain why royalty shares are usually low and almost never reach above 30% (Teece, 2000). In our symmetric Cobb-Douglas example, the royalty share is always below 50% or the mechanism falls apart).

Our model is also related to the literature on vertical integration and market foreclosure. Both Hart and Tirole (1990) and Bolton and Whinston (1993) consider an incomplete contract setting where an upstream firm may integrate with a downstream firm which may also have an impact on the other downstream firms. In particular, Hart and Tirole (1990) discuss the problem of commitment to exclusive sale where after selling to one downstream firm, the upstream firm may want to sell additional output to another downstream firm. Hart and Tirole discuss two solutions: integration and exclusive contracts. In the context of knowledge disclosure, both solutions have additional problems. Integration undermines the downstream firm's (DU's) incentives to exert effort; exclusive contracts are only enforceable through patenting which involves leakage. Bolton and Whinston (1993) study the case where downstream firms also invest. Yet, very much like Hart and Tirole (1990), and like Aghion and Tirole (1994), they understand vertical integration as allocation of residual rights of control over assets – an interpretation perfectly suitable for physical assets and product markets but less so for R&D.

Finally, our paper studies costs and benefits of corporate venturing vs independent venture financing. Kortum and Lerner (2001) have examined evidence on the impact of venture capital finance, including funding by corporate venturers, on the productivity of research by their RUs and their patenting activities; see also Gompers and Lerner (1998) for an exploration of corporate venturing. Hellman (2002) models RUs' optimal choices between independent vs corporate venture financing, based on (positive or negative) synergies between their targeted final inventions and the corporates' prior products. Our paper develops a new trade-off between corporate vs. independent venture capital financing, generating predictions on where corporate venturing should arise, and how corporate ventures should differ from independent RUs in terms of patent applications. We predict that research units financed (and controlled) by downstream development units are more likely to patent their interim innovations, as compared to those financed by independent venture capital.

7 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 use our framework to model corporate venturing as an ex ante transfer of ex interim decision rights. We show that although corporate venturing may reduce RU's flexibility and create ex interim inefficiencies, it may strengthen RU's ex ante incentives to generate knowledge when she is financially constrained. Thus corporate venturing may lead to a Pareto improvement for her and the licensee DU ex ante, via enhanced knowledge creation. The impact of ex ante research effort on the distribution of interim knowledge levels serves to determine whether corporate venturing improves welfare or not. Our thesis also has clear implications for patenting decisions by RUs controlled by DUs.

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.

For simplicity's sake we have assumed that a fixed share of knowledge is leaked in both open and closed modes. Our results would not change qualitatively if the share or probability of leakage is different in the two modes of disclosure. One can assume that while regulatory policies that weaken IPR protection may augment the leakage in the open mode, the degree of knowledge leakage in the closed mode is a benchmark technological parameter and is therefore unaffected by such legal changes.[17] Therefore, IPR-related regulatory policies should not affect the surplus in the closed mode. The relationship between IPR protection and R&D expenditures could thus still have an inverted U-shape, since the latter is driven by the effects of leakage on overall investment in the open mode combined with switching from the closed mode to the open mode as IPR protection increases. If the closed mode of knowledge sales matters a great deal in overall R&D activity, then our results would also be consistent with Kortum and Lerner (1998), who suggest that legislated changes in the protection provided via patents may have little impact on research related expenditures.

Throughout our paper, except in Section 5 on corporate venturing, 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.

An interesting avenue for further research is to study cooperation (e.g. via joint ventures) between the DUs. While the DUs are likely to compete ex post, there is a rationale for cooperative strategies at an earlier stages, in particular for coordinating payments to the RU in order to arrange multiple licensing. Our model may also be extended to analyze employment relationship in knowledge-intensive firms. There are obvious analogies between corporate researchers and RUs in our model, and between their (current and potential) employers and DUs. Yet, the roles of intra-firm authority, non-competing clauses, and non-pecuniary rewards (career concerns) as incentives to preclude opportunistic disclosure provide interesting avenues for further research. See Baccara and Razin (2004) for an interesting exploration of some of these issues.

Notes

1. 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).

2. 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.

3. 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.

4. 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

Hurwitz and Lie (1996). Sakakibara and Brensetter (2001) have analyzed Japanese evidence on this issue, based on the impact of patent reforms.

5. 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.

6. We use the symmetric Cobb-Douglas formulation for analytical tractability. Most our qualitative results hold for any neoclassical $p(K, E)$ with constant returns to scale.

7. We rule out patented sales to two DUs. One can 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. Indeed, in the latter case RU only gets half of the total surplus, while under an exclusive sale two DUs compete a la Bertrand for a single license, modulo the DUs' disagreement option of development based on leaked knowledge. Details of this simple proof are available upon request.

8. If the open mode is suboptimal ($T_o < T_c$), then the outside option can only bind for one party. Note that we treat DU$_i$'s open mode payoff as being an outside option rather than a disagreement option. 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).

9. One can easily show that $dE_o/dL > 0$ whenever $L > \Lambda(K) \equiv (3K-1)K^{-2}(3-K)^{-1}$. 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, while for $K \in (1/3, 1)$ effort is U-shaped with the minimum point at $L = \Lambda(K)$.

10. 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 when-

ever $\left[(1-L\widehat{K}(L))^2+L(1-\widehat{K}(L))^2\right]/(1-L\widehat{K}^2(L))^2 > (1-(1+L)/4)^2$. 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.

11. We assume that venture capital market is perfectly competitive so VC makes zero profit in equilibrium. The assumption that I can be financed without distortions is compatible with the prohibitive costs of financing independent development by RU; the investment in development may be much larger than I.

12. Once DU_i has observed the RU-VC coalition, the DU has incentives to impose the penalty so that VC's participation constraint does not hold. Anticipating this, VC will not join forces with the RU. We rule out the possibility of RU asking DU_i to renegotiate the penalty before contacting the VC. A stronger justification for this assumption arises when DU's expected payoff in the open mode of licensing $T_o - F_o$ is no lower than her symmetric share of the surplus in the closed mode $T_c/2$; in this case DU would not expected to be offered more than $T_o - F_o$ by the RU-VC coalition.

    We assume that for VC's reputational constraints to be effective, the RU-VC coalition must be formed before negotiations on licensing – otherwise there is a risk of opportunistic leakage of LK to the other DU_j by a VC whom RU approaches ex interim.

13. 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.

14. In two subsequent papers, Anton and Yao have extended their analysis to Incomplete interim information about RU's knowledge level, in which partial disclosure of knowledge serves as a costly signal thereof, as in Bhattacharya and Ritter (1983). In Anton and Yao (2002), this 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. 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*.

15. Dasgupta and Tao consider the possibility that a joint research venture may yield (as well as its original goal) unanticipated opportunities for further inventions that are asymmetric across its partners. They analyze the role of equity-based joint ventures with an exit or sale option for each partner, which facilitates their bargaining over the right to license the use of know-how developed in the joint venture in later inventions. Tepperman considers a setting in which two DUs may combine their efforts to develop a patented technology, which is however subject to the threat of costly imitation by the partner which is not initially assigned the property right to this patent. He shows that it is not necessarily optimal for the partner whose development effort is more productive to own this property right, when more valuable inventions are more likely to be imitated, especially when the imitation outcome is an Outside as opposed to an Ongoing or Disagreement option, as modeled in De Meza and Lockwood (1998).

16. A recent motion picture titled "The Paycheck," based on a science-fiction story by Phillip K. Dick, portrays a corporate researcher who is rewarded via cash and shares in his firm, but also has his memory erased after each discovery to ensure its non-disclosure to competitors, a technology that we rule out.

17. 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.

Appendix A. Proof of Proposition 1.

Let us first prove that if there is such $K^*(L)$ that $T_c(K^*(L);L) = T_o(K^*(L);L)$, then

$$\left(\frac{\partial T_c}{\partial K} - \frac{\partial T_o}{\partial K}\right)\Bigg|_{K=K^*(L)} > 0.$$

It suffices to establish that $\frac{T_c}{K/2}$ is strictly concave while $\frac{T_o}{K/2}$ is convex in K for a given L. Straightforward calculations show that this is the case.

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 (15) into (14) and (16), and using (6) 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 $D(0.68) = 0.18 > 0$. It is easy to check that $D(0) < 0$ and $D(1) < 0$. Therefore there exist such $L_1 \in (0, 0.68)$ and 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 $L_2 = 0.91$.

Appendix B. Impact of IPR protection on development expenditures

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 $K \in [0, 1]$:

$$g(K) = \frac{\lambda e^{-\lambda K}}{1 - e^{-\lambda}} \tag{19}$$

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 $\mathsf{E}K = \int_0^1 Kg(K)dK = \lambda^{-1} - \left(e^{\lambda} - 1\right)^{-1}$.

Figure 5 shows the relationship between IPR protection, proxied by $(1 - L)$, and the aggregate development expenditures for different values of λ, averaged out over $K \in [0, 1]$ according to the density function (19). 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 5 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.

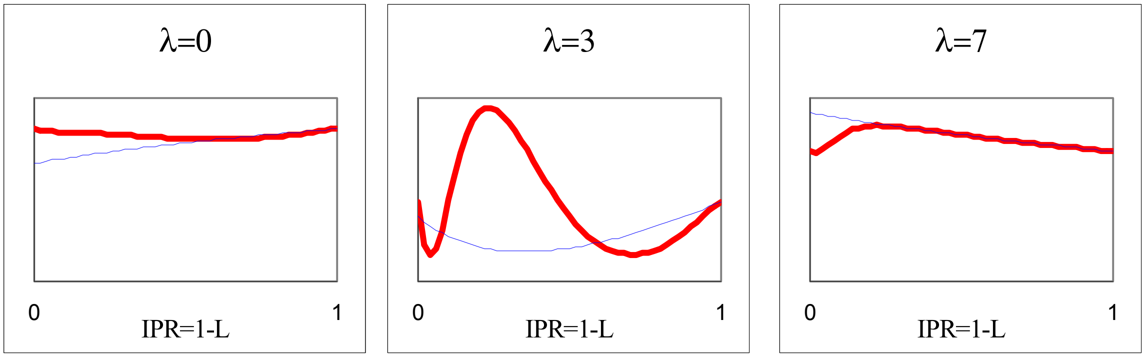

Figure 5: The thick line shows the aggregate development expenditures $E_1 + E_2$ as a function of IPR protection $(1 - L)$ given the equilibrium (i.e. ex interim privately optimal) mode of disclosure. The thin line is the aggregate development expenditure in the open mode (as if the closed mode were ruled out exogenously). The three parameter values are $\lambda = 0$ ($\mathsf{E}K = 0.5$, $g(1)/g(0) = 1$), $\lambda = 3$ ($\mathsf{E}K = 0.28$, $g(1)/g(0) = 0.05$), and $\lambda = 7$ ($\mathsf{E}K = 0.14$, $g(1)/g(0) = 0.0009$).

Total development expenditures 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 $(1 - L) \leq 0.5$. 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 effect (C) dominates for lower levels of $(1 - L)$, 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 $(1 - L)$ 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).

REFERENCES

Aghion, P. and J. Tirole (1994), "On the Management of Innovations", *Quarterly Journal of Economics*, 1185-1209.

Anand, B. and Galetovic, A. (2000), "Weak Property Rights and Holdup in R&D", Journal of Economics and Management Strategy 9, 615-642.

Anton, J. and D. Yao (1994), "Expropriation and Inventions – Appropriable Rents In the Absence of Property Rights", *American Economic Review* 84, 191-209.

Anton, J. and D. Yao (2002), " The Sale of Ideas: Strategic Disclosure, Property Rights, and Contracting", *Review of Economic Studies* 69, 513-532.

Anton, J. and D. Yao (2004), " Little Patents and Big Secrets: Managing Intellectual Property", *Rand Journal of Economics* 35, 1-22.

d'Aspremont, C., Bhattacharya, S. and Gerard-Varet, L.A. (2000), "Bargaining and Sharing Innovative Knowledge", *Review of Economic Studies* 67, 255-271.

Baccara, M., and Razin, R. (2002), "From Thought to Practice: Appropriation and Endogenous Market Structure with Imperfect Intellectual Property Rights", *Mimeo*, NYU.

Baccara, M., and Razin, R. (2004), "Curb Your Innovation: Corporate Conservatism in the Presence of Imperfect Intellectual Property Rights" , *CEPR Discussion Paper 4466*, London.

Bank, D. (1997), "Spyglass is hurt in royalty flap with Microsoft", Wall Street Journal (Eastern Edition). New York, N.Y.:Jan 3, 1997. p. B, 3:1.

Bessen, J. and Maskin, E. (2000), "Sequential innovation, Patents and Imitation", Massachusetts Institute of Technology Working Paper No. 00-01, Cambridge, MA.

Bhattacharya, S. and Ritter, J. (1983), "Innovation and Communication: Signalling with Partial Disclosure", *Review of Economic Studies* 50, 331-346.

Bhattacharya, S., Glazer, J. and Sappington, D. (1992), "Licensing and the Sharing Of Knowledge in Research Joint Ventures", J*ournal of Economic Theory* 56, 43-69.

Bhattacharya, S. and Chiesa, G. (1995), "Proprietary Information, Financial Intermediation, and Research Incentives", *Journal of Financial Intermediation* 4, 328-357.

Bolton, P. and Whinston, M. (1993), "Incomplete Contracts, Vertical Integration, and Supply Assurance", *Review of Economic Studies* 60, 121-148.

Chang, H. (1995), "Patent Scope, Antitrust Policy, and Cumulative Innovation", *RAND Journal of Economics* 26, 34-57.

Cohen, W., Nelson, M. and Walsh, J.P. (2000), "Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not)", *National Bureau of Economic Research Working Paper No. 7552*, Cambridge, MA.

Cornelli, F. and Yosha, O. (2003), "Stage Financing and the Role of Convertible Securities", *Review of Economic Studies* 70, 1-32.

Dasgupta, S. and Tao, Z. (1998), "Contractual Incompleteness and the Optimality of Equity Joint Ventures", *Journal of Economic Behavior and Organization* 37, 391-413.

De Meza, D. and Lockwood, B. (1998), "Does Asset Ownership Always Motivate Managers? Outside Options and the Property Rights Theory of the Firm", *Quarterly Journal of Economics*, 361-386.

Denicolo, V. and Franzoni, L. (2004), "Patents, Secrets, and the First-Inventor Defense", *Journal of Economics and Management Strategy 13(3)*, 517–538.

Featherstone, J. and Renfrey, S. (2004), "Licensing Gambles: Raising the Stakes", *Nature Reviews: Drug Discovery*, vol. 3, 107-108.

Paolo Fulghieri, P. and Sevilir, M. (2003), "The ownership and financing of innovation in R&D races", http://papers.ssrn.com/sol3/papers.cfm?abstract_id=397500

Gallini, N. (2002), "The Economics of Patents: Lessons from Recent U.S. Patent Reforms", *Journal of Economic Perspectives* 16, 131-154

Gompers, P. and Lerner, J. (1998), "The Determinants of Corporate Venture Capital Successes", in R. Morck (ed.), *Concentrated corporate ownership.* University of Chicago Press.

Green, J. and Scotchmer, S. (1995), "On the Division of Profits in Sequential Innovation", *RAND Journal of Economics* 26, 20-33.

Grossman, S. and Hart, O. (1986), "The Costs and Benefits of Ownership: a Theory of Vertical and Lateral Integration", *Journal of Political Economy* 94, 691-719.

Hart, O. (1995), *Firms, Contracts, and Financial Structure*, Clarendon Press, UK.

Hart, O. and Moore, J. (1990), "Property Rights and the Nature of the Firm", *Journal of Political Economy* 98, 1119-1158.

Hart, O. and Moore, J. (2004), "Agreeing Now to Agree Later: Contracts that Rule Out but do not Rule In", mimeo, Harvard.

Hart, O. and Tirole, J. (1990), "Vertical Integration and Market Foreclosure", *Brookings Papers: Microeconomics*, 205-276.

Hellmann, T. (2002), "A Theory of Strategic Venture Investing", *Journal of Financial Economics* 64, 285-314.

Hensley, S. (2003), "GlaxoSmithKline to Showcase Strides in Research Productivity", *Wall Street Journal (Eastern edition).* New York, N.Y.: Dec 3, 2003. p. D9

Horwitz, A. and Lai, E. (1996), "Patent Length and the Rate of Innovation", *International Economic Review* 37, 785-801.

Jensen, R. and Thursby, M. (2001), "Proofs and Prototypes for Sale: The Licensing of University Inventions", *American Economic Review 91*, 240-259.

Klein, B., Crawford, R., and Alchian, A. (1978), "Vertical Integration, Appropriable Rents, and the Competitive Contracting Process", Journal of Law and Economics 21, 197-326.

Kortum, S. and Lerner, J. (1998), "Stronger Protection or Technological Revolution: What is Behind the Recent Surge in Patenting?", *Carnegie-Rochester Conference Series on Public Policy* 48, 247-304.

Kortum, S. and Lerner, J. (2001), "Venture Financing and R&D", *RAND Journal of Economics* 32.

Lerner, J. (2001), "150 Years of Patent Protection: an Empirical analysis", *Harvard Business School Working Paper no. 8656*, Boston, MA.

Lai, E., Riezman, R., and Wang, P. (2003), "Outsourcing of Innovation", *Mimeo*, University of Iowa.

Lester, G.L.L., and Talley, E.L. (2000), "Trade Secrets and Mutual Investments", *Olin Research Paper No. 00-15*, USC Law School.

LLOBET, G., HOPENHEYN, H. AND MITCHELL, M.(2000), "Rewarding Sequential Innovators: Prizes, Patents and Buyouts", *University of Rochester Working Paper.*

MORAIS, R. C. (2003), "Mind The Gap", *Forbes.* New York: Aug 11, 2003.Vol. 172, Iss. 3; p. 58.

NAIK, G. (2002), "GlaxoSmithKline Actively Pursues Drug License", *Wall Street Journal (Eastern edition).* New York, N.Y.: Feb 13, 2002. p. B2

NEW YORK TIMES (2004), "Inventor Wins a Round in Tokyo Court", Jan 31, 2004.

NOLDEKE, G., AND SCHMIDT, K. (1998), "Sequential investments and options to own", *Rand Journal of Economics* 29(4): 633-653.

PISANO, G. (1989), "Using Equity Participation to Support Exchange: Evidence from the Biotechnology Industry", *Journal of Law, Economics, and Organization* 1, 109-26.

ROSENKRANZ, S., AND SCHMITZ, P. (1999),"Know-How Disclosure and Incomplete Contracts", *Economics Letters* 2, 181-185.

ROSENKRANZ, S., AND SCHMITZ, P. (2002),"Optimal Allocation of Ownership Rights in Dynamic R&D Alliances", *Games and Economic Behavior* 43, 153-173.

RUBINSTEIN, A. (1982), "Perfect Equilibrium in a Bargaining Model", *Econometrica* 50, 97-110.

SAKAKIBARA, M. AND BRANSTETTER, L. (2001), "Do Stronger Patents Induce More Innovation? Evidence from the 1988 Japanese Patent Law Reforms", *RAND Journal of Economics* 32, 77-100.

SCOTCHMER, S. AND GREEN, J. (1990), "Novelty and Disclosure in Patent Law", *RAND Journal of Economics* 21, 131-146.

SPENCE, M. (1984), "Cost Reduction, Competition, and Industry Performance" *Econometrica* 62, 101-121.

SRIKANTH, R. (2003), "Should Indian IT dive into IP licensing?", *Express Computer India,* Sep 1, 2003.

STAHL, I. (1977). "An N-Person Bargaining Game in the Extensive Form", in R. Hehn and O.Moeschlin (ed.) *Mathematical Economics and Game Theory*, Springer Verlag, Berlin.

TEECE, D. (2000), *Managing Intellectual Capital*, Oxford University Press, UK

TEPPERMAN, A. (2000), "Intellectual Property Rights in a Theory of the Firm", University of Toronto Working Paper, Canada.

WILLIAMSON, O. (1971), "The Vertical Integration of Production: Market Failure Considerations", *American Economic Review* 61, 290-306.

WILLIAMSON, O. (1976), *Markets and Hierarchies,* The Free Press, NY.

WOOD MACKENZIE (2004), "Licensing Insight 04", Wood Mackenzie consulting, Boston and Edinburgh.