PATENTS VS. TRADE SECRETS: KNOWLEDGE LICENSING AND SPILLOVER

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Abstract
We develop a model of two-stage cumulative research and development (R&D), in which one research unit (RU) with an innovative idea bargains to license its nonverifiable interim knowledge exclusively to one of two competing development units (DUs) via one of two alternative modes: an open sale after patenting this knowledge, or a closed sale in which precluding further disclosure to a competing DU requires the RU to hold a stake in the licensed DU's postinvention 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. The open sale is socially optimal; yet the contracting parties choose the closed sale whenever the interim knowledge is more valuable and leakage is sufficiently high. If the extent of leakage is lower, more RUs choose open sales, generating a nonmonotonic relationship between the strength of intellectual property rights and aggregate R&D expenditures and the overall likelihood of development by either DU. (JEL: 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) engages in research to produce an interim innovative idea ("knowledge"). The idea has no value to consumers, but it could be developed further into a marketable product by one of two competing development units (DUs, e.g., large pharmaceutical companies).

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The latter are assumed to be far more efficient in developing the idea than the original research unit itself, by virtue of having deep pockets, which would enable them to avoid the incentive losses arising from external financing of development costs and/or via owning specific complementary assets or skills. We study the key trade-offs between different mechanisms for selling or licensing such ideas, involving patenting of the knowledge or relying on trade secrets. We then characterize when each of these licensing mechanisms is more likely to be chosen and derive the implications of these choices for the structure of licensing fees. In particular, we focus on contractual choices over (combinations of) lump-sum versus revenue-contingent royalties, taking into account their impact on development incentives, and the viability of exclusive licensing of interim innovative knowledge.

These issues are certainly important in a modern economy. As Scotchmer (1991, p. 24) 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% 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. For example, since 2000, GlaxoSmithKline has pursued a new approach to R&D and has moved from two or three in-licensing deals per year to more than 10 per year (Morais 2003). Their restructuring paid off and other firms followed their example, engaging in late- and early-stage licensing deals (Featherstone and Renfrey 2004).

In other industries, such sequential innovation is also important, though the nature of licensing arrangements varies greatly; outside of a small set of industries (including biotech) the sellers of knowledge rely on secrecy rather than on patents (Cohen, Nelson, and Walsh 2000). Also, inventors are paid in cash, in stock, through participation in joint ventures, or via revenue-contingent royalties. For example, while purchasing software technology for its Internet Explorer web browser from Spyglass, Microsoft agreed to pay Spyglass about $1 per 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).

Several issues concerning the licensing of such intellectual property are of substantial interest. Why do both in-house and in-licensed research coexist? Why are some sales of ideas based on patents and others on trade secrets? What are the roles of lump-sum fees versus contingent royalty payments in providing incentives for R&D, and for exclusive licensing?

We attempt to answer some of these questions within an incomplete contract setup where two potential buyers of nonverifiable knowledge compete to obtain a license to develop the knowledge. Unlike conventional incomplete contract models, we take into account not only the fact that the value of such knowledge is not verifiable, but also the imperfect excludability and nonrivalrous nature of knowledge. Imperfect excludability implies that after an item of knowledge is described to a potential buyer, he immediately captures a certain share of its potential value. Indeed, utilization of at least part of the idea is a credible threat which may weaken the seller's bargaining position. On the other hand, the nonrivalrous nature of knowledge makes it difficult for the seller to commit to an exclusive sale: After selling knowledge to one buyer, the seller can sell it again to another buyer. We explore the implications of alternative licensing mechanisms that enable the seller to commit to exclusivity.

A conventional approach to assuring exclusivity is via patenting. Teece (2000 p. 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." As Teece notes, 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 inventions. As a result, the licensor of patented interim knowledge finds it much easier to precommit to exclusive licensing thereof. If she were to sell her knowledge to another developer, his final invention would embody the same look and feel as the aspects of the knowledge codified in the patent, and it would be thus denied a final invention patent. Of course, in reality such enforcement of patents is only probabilistic, as in Anton and Yao (2004), but for simplicity we will assume that patenting is a perfect means for exclusion.

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

The alternative arrangement is to sell the knowledge privately, relying on trade secrets. Trade secrets do not involve putting the description of the invention in the public domain and therefore avoid the above-mentioned knowledge spillovers. However, without patents it is difficult for the seller to commit to an exclusive sale. Upon selling the innovation, the seller has incentives to resell the knowledge to a competing buyer. The existing literature on collaborative research (e.g., Pisano 1989, ch. 3; Oxley 1999; Teece 2000; Majewski 2004) recognizes the risk of such opportunistic disclosure as an important factor shaping the contractual environment and organizational structure.[1] Indeed, it is difficult to punish the seller of the knowledge for the second sale. Courts may refuse to enforce contracts that stipulate a penalty for the knowledge seller in case of invention by a developer other than her licensee, as long as they believe that this developer might have originated similar knowledge on his own. As Denicolo and Franzoni (2004a, p. 367) note, "Trade secret law does not protect the inventor from independent rediscovery," and that is exactly what this developer, who in fact benefited from a second sale of knowledge by the RU, would claim.

We consider a more realistic mechanism for committing to exclusive sale without patents. The original buyer gives the researcher a share of its future revenues (through an equity stake or through royalties).[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.[3] Stakes are even higher in biotech-pharmaceutical licensing: Hoffmann-La Roche's recent deal with Antisoma included a lump-sum payment of \$43 million plus 10–20% 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). If the seller's revenue share is sufficiently high, the seller would prefer not to sell the knowledge

1. Teece (2000) and Pisano (1989) argue that in order to solve the problem of opportunistic use of information, the parties should form alliances that provide adequate incentives through equity participation (similar to the contingent contracts in our model). Majewski (2004) shows that the risk of misappropriation of knowledge is substantial and it often results in limits on personnel exchange in cooperative R&D. Oxley (1999) shows that the risk of opportunistic use of ideas shapes organizational form of international R&D companies (consistent with our model's predictions, the higher the risk the more equity participation).

2. 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. "Inventor Wins a Round in Tokyo Court," *New York Times*, January 31, 2004 Business Digest, C3.

to the first buyer's competitors, because the value of the RU's royalty stake is contingent on the first buyer achieving a monopoly position in the product market. Although others such as Pisano (1989) have also suggested a linkage between the co-ownership of equity shares and preventing harmful opportunistic knowledge disclosure, we are the first to fully analyze this mechanism taking into account its effects on both buyers' and sellers' incentives.[4]

Even though this share-based mechanism (which we call the "closed" mode of licensing) assures exclusive licensing, it does not come free of charge. The buyer's incentive to invest in development is more severely undermined the higher the share of his final revenues he has to give away to the knowledge seller. We show that this mechanism works better when the original idea is highly valuable. The more valuable the knowledge, the higher is the probability of final invention by an exclusive licensee. Hence, a clandestine sale of knowledge to a second developer greatly diminishes the value of the knowledge seller's expected revenue share in the original licensee, by sharply lowering his prospects for sole invention. As a result, for a higher level of knowledge the seller is induced to abide by an exclusive license for a smaller share in the licensee's future revenues. The buyer keeps a higher share of his future revenue, which results in more efficient investment in further development. Moreover, as we formally show, for the least valuable ideas this revenue share mechanism ceases to function. If the seller's revenue share is low, the seller has an incentive to resell the knowledge to the competing buyer; if it is high, the buyer does not invest much in development of the idea. The value of the exclusive licensee is low, and the seller has no incentive to abide by exclusivity.

We explicitly model the extensive form bargaining between the parties in the patent-based and trade-secret-based modes of licensing, and find that the parties are more likely to choose the nonpatented (or "closed") mode of licensing over patenting if the interim knowledge is highly valuable, and if describing the knowledge involves substantial leakage. The intuition for the latter effect is straightforward. On one hand, greater leakage in the patenting process makes patenting a less attractive option. On the other hand, in closed sales, greater leakage via private description of knowledge is helpful, as then the seller would have a weaker bargaining position in a clandestine opportunistic sale to the competitor of the original buyer. As a result, a lower revenue share from the original licensee would suffice to dissuade her.

4. After writing the first draft of this paper, we have also become aware of Lai, Riezman, and Wang (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, whereas we explicitly model a development race. 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. Although our closed mode of knowledge sales is based on a similar idea, unlike Baccara and Razin (2002) we model our RU's stake in her licensee DU's ex post revenue as being contractible.

The explanation for more valuable knowledge being licensed privately follows from the detailed comparison of incentives in a revenue-contingent royalty contract, with those arising via patenting before licensing. This comparison takes into account two major effects. The first one is that the share of future revenue that RU has to be given to assure no second sale is decreasing in the level of knowledge. Thus, RU and her licensee DU capture a higher (but diminishing in slope) proportion of the full potential value of interim knowledge as its level increases.

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

Even though the trade-secret-based licensing is chosen for the more valuable and less codifiable ideas, we show that it is socially suboptimal to the patent-based mode. Indeed, the licensor-licensee coalition neglects the nonlicensee's welfare due to public knowledge disclosure via patents and the consumer surplus due to product market competition between licensee and nonlicensee DUs.

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

We then consider the implications of our results for the impact of intellectual property protection—either legally as determined by the stringency and enforcement of patents (IPR), or as determined by the nature of the technology that is described prelicensing—on the overall extent of development expenditures, as well as their productivity, aimed at final invention. We show that the trade-offs we analyze may suffice to generate nonmonotonic relationships between the strength of intellectual property protection (including IPR) and aggregate R&D expenditures. In particular, depending on the ex ante distribution of the interim knowledge levels, an interior degree of such protection may maximize overall levels and efficacy of development efforts, when endogenous choices over licensing modes are allowed, but that is not the case when attention is restricted to patented sales.

Earlier theoretical models pertaining to endogenous expenditures on imitation as well as innovation, in the context of patented final inventions, have suggested the possibility of a nonmonotonic, indeed ∩-shaped, relationship between the strength of IPR protection as measured by patent length and R&D activity.[5] A recent empirical study by Lerner (2001) provides some support for this conjecture. In our model, such an ∩-shaped relationship between the strength of intellectual property protection—measured as the complement of the extent of knowledge leakage prelicensing—emerges more simply, from the impact of such protection on endogenous choices over knowledge licensing modes at different levels of knowledge.

Our analysis develops the application of the incomplete contracting paradigm by Grossman and Hart (1986) to the issues of incentive for R&D started by Aghion and Tirole (1994), who analyzed knowledge licensing fees and their implications for incentives to expend noncontractible efforts or invest in research and development, by a RU incapable of development and a single DU incapable of first-stage research. We also extend the important work of Anton and Yao (1994), which considered rent extraction by an RU from a DU based on a threat of knowledge disclosure to a competing DU, when leakage of knowledge arising from its description is complete.[6]

Our paper is also related to the literature on foreclosure, exclusive dealing, and vertical integration, surveyed in Rey and Tirole (forthcoming). The latter is also concerned with the problem of precommitment, when a monopolistic upstream

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

6. 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. There are also recent papers by Jansen (2005) and Gill (2006), who show that leakage can be strategic as it can actually weaken the competitors' incentives to invest in development.

supplier can sell an intermediate input to multiple competing final goods producers downstream. The upstream firm seeks to extract as much surplus as possible, via strategic pricing of the input. In particular, several authors (for example, McAfee and Schwartz 1994), model the possibility of the upstream firm making secret input supply offers to a second downstream firm after reaching an agreement with the first firm, and then elaborate on mechanisms such as vertical integration to internalize the externalities involved. Our revenue-sharing mechanism for knowledge sales based on trade secrets shares a similar flavor, as does a mechanism analyzed by Cestone and White (2003) in which giving equity shares to a monopolistic lender may dissuade her from financing competing entrants. Our main contributions are to consider also the alternative mechanism of patenting, which also enables commitment to exclusive licensing and characterize how choices across these mechanisms depend on some salient features of interim knowledge.

The rest of the paper is organized as follows. In Section 2, we set up our model, describing its notation, timing, and the protocols of bargaining processes involved in knowledge licensing. In Section 3, we characterize the equilibrium choices over modes of licensing, and structure of fees across RU and her licensee DU. In Section 4, we study comparative statics with respect to the degree of protection of intellectual property, both analytically and numerically. Section 5 concludes.

2. The Model

2.1. The Setup

There are three risk neutral agents: a research unit RU and two competing development units DU_1 and DU_2. These parties undertake research (by RU) and development (by DUs) to create a new product. The investments in research and development are sequential. First, RU produces knowledge K. This knowledge has no value per se but is an input in the development stage that 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 à la Bertrand and both get zero rents. In this paper, we do not focus on the knowledge generation process and take the level of knowledge $K \in [0, 1]$ as given. We assume K to be the outcome of an exogenous random process with a density known ex ante.

For each DU, his probability P of successful development is a strictly increasing and concave function of his acquired knowledge and subsequent costly noncontractible development effort choice. For analytical tractability, we focus on a functional form that allows us to characterize the equilibrium choices of P_i by a DU_i as linear functions of DU_j's choice P_j, as well as RU's ex post revenue share. The intuition behind our results, elaborated in the Introduction

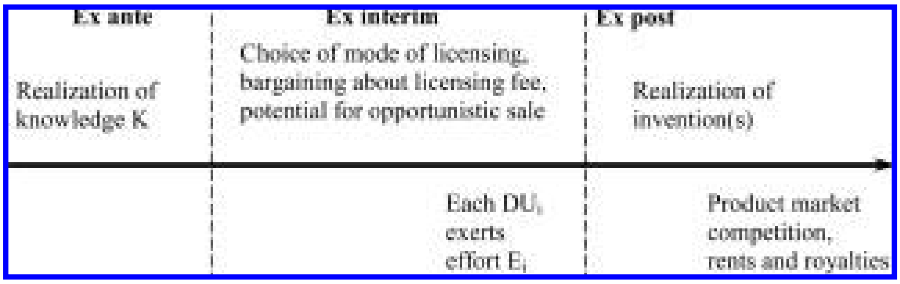

FIGURE 1. Timing.

and subsequently, should hold for a wider range of such development probability functions. We define, for effort levels $E \in [0, 1/2]$:

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

The development effort E is measured in terms of its cost. These are assumed to be nonverifiable. 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 this constraint is never binding.

2.2. Timing

The timing of events is presented in the Figure 1.

Ex ante. RU obtains knowledge K.

Ex interim. The parties choose the mode of licensing of RU's knowledge—open or closed—and then bargain on the licensing fee contract.

Ex post. Successful developers compete à la Bertrand. If only one DU invents successfully, he obtains a monopoly rent of $V = 1$. If both develop successfully, both get zero ($V = 0$), which is also their payoff if neither invents.

2.3. Licensing Modes

The two alternative modes of knowledge licensing evolve as follows. (The bargaining game in each mode, with and without patenting, is described in Sections 2.4 and 2.5.)

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

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

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

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

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

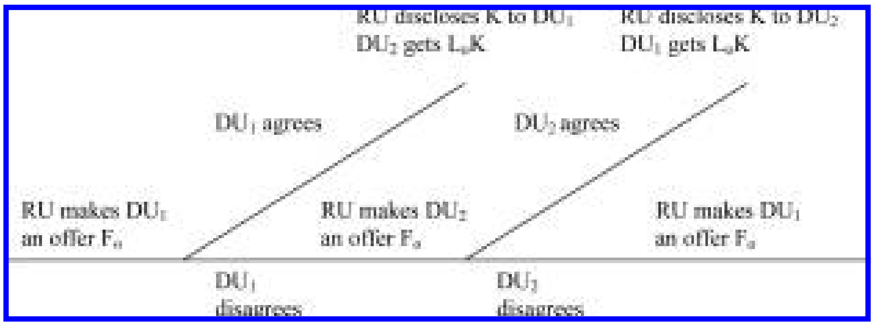

FIGURE 2. Bargaining in the open mode.

reaching agreement on a licensing contract. If that is not the case, then L_c is likely to exceed L_o.[7] We should emphasize that even if $L_c > L_o$, in equilibrium the spillover is greater in the open mode as the information is leaked to the public domain, while in the closed mode only the buyer of the knowledge receives it.

2.4. Bargaining in the Open Mode

The multilateral bargaining game in the open mode is similar to the one in Bolton and Whinston (1993). RU and the DUs bargain about full disclosure of knowledge K. After patenting, RU makes an offer to DU_i. The offer specifies the payment F_o for the exclusive disclosure of knowledge K to DU_i. DU_i either accepts or declines the offer. In the former case, DU_i develops on the basis of K, whereas the competing DU_j only has access to the leaked knowledge LK. If DU_i declines RU's offer, RU makes an offer to DU_j and so on (Figure 2). We analyze an infinite horizon bargaining game, with parties having a common discount rate $\delta \to 1$.

Once the agreement on the terms of disclosure is reached, $\mathrm{DU}_{1,2}$ choose their postlicensing levels of development effort $E_{1,2}$ (equivalently, their probabilities of successful development $P_{1,2}$), as detailed previously.

We rule out patented sales to both DUs. We shall show that in the resulting tripartite bargaining (e.g., see Bolton and Whinston 1993) this is always dominated from RU's point of view by an exclusive knowledge sale to one DU. The RU is better off with the exclusive sale, even when licensing to both DUs may increase total developers' surplus ex interim. The rationale is that in the latter case

7. However, in some cases patenting may involve a greater extent of knowledge leakage than private sales $L_o < L_c$. 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.

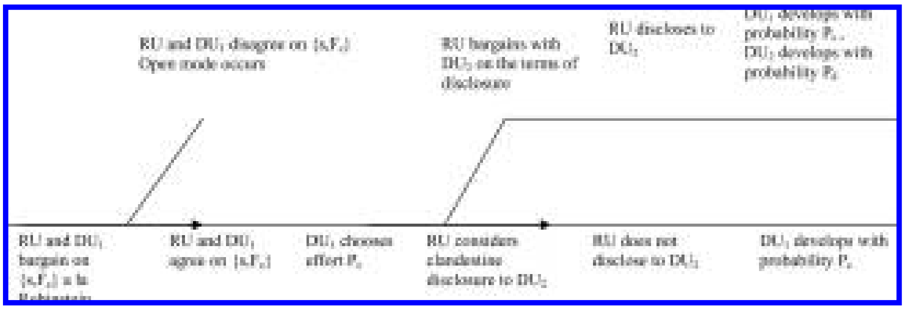

FIGURE 3. Bargaining in the closed mode. Arrows indicate the equilibrium path.

RU would only get half of this total surplus, while under an exclusive sale the two DUs compete à la Bertrand for a single license, modulo the DUs' disagreement option of development based on leaked knowledge. A formal proof is provided in Section 3.

2.5. Bargaining in the Closed Mode

RU randomly chooses DU_i to arrange a private sale. The bargaining in the closed mode is a conventional bilateral alternating offer game as in Rubinstein (1982): RU makes an offer of $\{s, F_c\}$; if DU_i declines, it makes a counteroffer, and so on (Figure 3).

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

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

2.6. Interim Payoffs

We will denote as T_c and T_o the total equilibrium ex interim expected surplus of RU-cum–the licensee DU obtaining the full knowledge in the closed and in the open mode, respectively. We will denote as $U_{oi}(P_i, P_j; K)$ the expected ex interim payoff of this DU in the development race in the open mode, whereas the other DU$_j$ chooses probability of invention P_j to maximize $U_{oj}(P_j, P_i; L_o K)$. According to (1), DU$_i$'s effort cost is $E_i = P_i^2/(2K)$ so that in the open mode

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

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

$$U_{oj} = \left[(1 - P_i)P_j - P_j^2/(2L_o K)\right]$$

by choosing $P_j = L_o K(1 - P_i)$.

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

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

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

2.7. *Choice over Licensing Modes*

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

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

The other case is where K is such that the level of RU's required revenue share s to ensure an exclusive closed-mode sale is so high that RU has to make a lump-sum payment to her licensee DU$_i$, $F_c < 0$, to make DU$_i$ accept a closed sale over a patented one. As RU's wealth constraint precludes her making the payment, the parties may choose to patent the knowledge even though $T_c > T_o$.

This happens whenever $T_c - sP_c < T_o - F_o$. We consider further implications of this case in a companion paper (Bhattacharya and Guriev 2005).

3. Equilibrium Outcomes

In this section, we characterize the equilibrium payoffs of the RU and the DUs under the alternative modes of disclosure at the ex interim stage. First, we derive the joint surplus of the RU and her licensee DU_i in the open and closed modes of disclosure, $T_o(K, L_o)$ and $T_c(K, L_c)$, respectively. Then we study the choice of licensing mode and describe the division of the surplus between RU and DU_i. All proofs are contained in the Appendix.

3.1. Open Mode

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

$$P_o = \arg\max_p [(1 - Q_o)p - p^2/(2K)] = K(1 - Q_o),$$

$$Q_o = \arg\max_p [(1 - P_o)p - p^2/(2L_oK)] = L_oK(1 - P_o).$$

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

$$P_o = \frac{K(1 - L_oK)}{1 - L_oK^2} \quad \text{and} \quad Q_o = \frac{L_oK(1 - K)}{1 - L_oK^2}. \tag{4}$$

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

The RU's fee F_0 is determined as the outcome of the sequential offer bargaining game described in the Section 2.4 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*

$$U_o \triangleq U_{oj}(Q_o, P_o; L_o K) = [(1 - P_o)Q_o - Q_o/(2L_o K)],$$

while RU obtains

$$F_o = \left[P_o(1 - Q_o) - P_o^2/(2K)\right] - \left[(1 - P_o)Q_o - Q_o^2/(2L_o K)\right]$$

from DU_i.

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

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

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

Both $T_o(K, L_o)$ and $F_o(K, L_o)$ increase in K and decrease in L_o for all $K, L_o \in [0, 1]$. On the other hand, either DU's payoff U_o increases with L_o. Indeed, the licensee DU receives her reservation utility which is equal to the payoff of a nonlicensed 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 $K \to 1$ for all $L_o < 1$. This is an implication of the nonmonotonic relationship between K and the nonlicensee's effort Q_o discussed above.

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

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

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

3.2. Closed Mode

If the contracting parties do not register a patent but choose disclosure via a closed sale, there is no leakage to outsiders in equilibrium. However, in order to provide RU with incentives not to disseminate knowledge to the competing DU_j, DU_i has to give away a sufficient share s of his ex post revenues in royalties to RU. The formal condition is that the reduction in the RU's royalties due to opportunistic disclosure to DU_j must weakly exceed the maximum fee that RU may get from DU_j:

$$sP_c - sP_c(1 - P_d) \geq \left[(1 - P_c)P_d - \frac{P_d^2}{2K}\right] - \left[(1 - P_c)Q_d - \frac{Q_d^2}{2L_cK}\right], \quad (6)$$

where P_c is chosen by the licensee DU_i and $\{P_d, Q_d\}$ are the potential choices of the other DU_j if the RU attempts to sell knowledge to her. P_d would be chosen by DU_j if she had full knowledge, and Q_d would be her choice with leaked knowledge L_cK.

For a given share s, the left-hand side in (6) is the reduction in the RU's payoff because of 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: Because the process of negotiating the fee results in a partial leakage of knowledge L_cK, RU can obtain from DU_j at most the expression in the right-hand side. If and only if (6) is violated, there exists a fee that DU_j will be willing to pay and RU will be willing to accept in exchange for the clandestine second sale. RU's incentives for exclusive disclosure come from the fact that selling the knowledge to a competing DU_j dilutes the DU_i's expected payoff and thus reduces the value of RU's royalty stake from sP_c to $sP_c(1 - P_d)$ as described in the left-hand side of (6).

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

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

$$Q_d = \arg\max_q \left[(1 - P_c)q - q^2/(2L_cK)\right] = L_cK(1 - P_c); \quad (8)$$

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

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

$$sP_cP_d \geq K(1 - P_c)^2/2 - L_cK(1 - P_c)^2/2. \tag{10}$$

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

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

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

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

The licensee DU develops with probability $P_i = P_c = K(1 - s^*(K; L_c))$, *the other DU does not develop.*

This closed mode licensing is only feasible if such $s^*(K; L_c)$ *exists, that is, whenever* $K \geq \hat{K}(L_c)$, *where*

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

This result is intuitive; the monopoly 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 $K < \hat{K}(L_c)$, then the private disclosure to one DU cannot be arranged because of the adverse incentive effect on DU's effort. In order to increase the RU's stake, DU_i gives RU a higher share s. However, as s increases, DU_i's effort decreases, so that P_c falls. Hence, the competing DU_j is prepared to pay more for the knowledge: the lower P_c, the higher the payoff to DU_j's effort. At lower levels of interim knowledge $K < \hat{K}(L_c)$, RU's returns to opportunistic disclosure (the right-hand side in [6]) increase in s so rapidly that the benefits of keeping DU_i a monopoly (the left-hand side in [6]) never catch up with it. Because $P_c = K(1-s)$, sP_c reaches its maximum at $s = 1/2$, implying $s^*(K; L_c) \leq 1/2$. The closed mode is feasible over a larger range of K when leakage L_c is high, because RU's payoff from a deviant second sale declines when L_c increases. Indeed, $\hat{K}(L_c)$ decreases in L_c from $\hat{K}(0) = 8/9$ to $\hat{K}(1) = 0$.

Whenever the closed mode is incentive-compatible, the RU's share $s^*(K; L_c)$ decreases with K and with L_s. The higher K, the higher the payoff to the monopoly development. Because 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.[8] Clearly, whenever $s = s^*(K; L_c)$ exists, it decreases in K, and so that right-hand side of (11) decreases in K. Therefore the left-hand side $sK(1-s) = sP_c$ also decreases in K. The joint surplus of RU and DU_i

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

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

Unlike in the open mode where the joint surplus of RU and the licensed DU_i decreases in leakage L_o, joint surplus T_c in the closed mode increases with L_c. If L_c is higher, RU would receive less from the competing DU_j; the opportunistic disclosure option is less attractive. Hence, DU_i can give RU a lower share of ex post revenues; his development effort and probability of successful development P_c rise. This also leads to a higher joint surplus $T_c(K, L_c)$ when L_c rises, because the share $s^*(K; L_c)$ falls (see equation [14]). If the leakage L_c is low then the closed mode is only feasible for very high K; as shown above for $L_c = 0$, the closed mode only exists at $K \geq 8/9$.

3.3. The Choice of the Mode of Disclosure

In this section, we show that the parties choose the closed mode over the open mode if L_o, L_c, or K are sufficiently high. If the leakages L_o, L_c are low, the open mode dominates the closed mode. If L_o is close to zero, the joint surplus of RU and DU_i is not undermined by the competing DU_j; ex interim joint surplus T_o is close to its maximum $\max_p[p - p^2/(2K)] = K/2$. Moreover, for low L_c the risk of opportunistic disclosure in the closed mode is high, so DU_i has to give RU a very high revenue share; hence his probability of successful development is lowered. As the leakage in either mode rises, open sales become less efficient, while closed sales produce a higher surplus to RU and licensee DU_i.

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

The closed mode is also more efficient for high K. The higher K the more valuable the monopoly DU's rent, hence the threat of opportunistic disclosure in the closed mode is less important. On the other hand, if K is low, $K < \hat{K}(L_c)$, then a private sale to one DU is infeasible ($s^*(K; L_c)$ does not exist), so the open mode is chosen. These observations can be generalized, to the following single-crossing property of the impact of K on the combined surpluses of RU and DU in each mode (Figure 4).

PROPOSITION 1. *If the closed mode of knowledge sale is more efficient for RU–DU$_i$ coalition for some $\tilde{K}$, then it is also more efficient for all $K \geq \tilde{K}$. There exists a $K^*(L_o, L_c) \geq \hat{K}(L_c)$ such that $T_c \geq T_o$ for all $K \geq K^*(L_o, L_c)$, whereas if $K < K^*(L_o, L_c)$ the closed mode either does not exist or is dominated by the open mode $T_c < T_o$.*

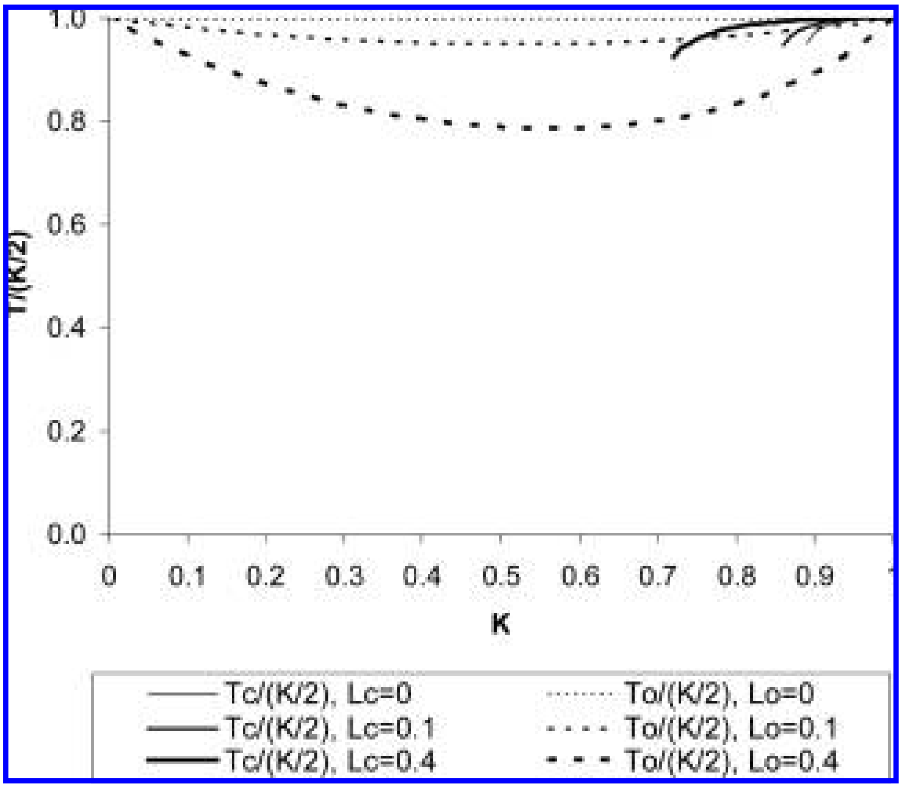

FIGURE 4. The graph presents joint surplus as a share of $K/2$ (i.e., surplus if there were no leakage in the open or no threat of second sale in the closed mode). In the closed mode, $T_c/(K/2)$ is concave in K, whereas in the open mode $T_o/(K/2)$ is convex in K.

For different combinations of leakage coefficients L_o, L_c, the comparison of $T_c(K; L_o)$ and $T_o(K; L_c)$ satisfies one of three cases (Figure 4).

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

The parties' payoffs depend both on the joint surplus and on their outside options. The RU has an outside option of choosing the open mode of knowledge sale with payoffs $\{F_o, T_o - F_o\}$ to RU and DU_i, respectively. Once the IPR is registered, in the form of a patent, the two parties cannot return to private sales. The DU_i's outside option is more complex. If $L_c \geq L_o$, once the closed mode bargaining begins, DU_i can ensure a payoff of $T_o(K; L_c) - F_o(K; L_c)$. If DU_i is made an offer with a lower payoff, then DU_i would reject RU's closed mode offer; as DU_i has already obtained leaked knowledge $L_c K$, RU's best continuation strategy is to patent the knowledge and to license it to DU_i. To simplify the solution of the game, we consider the case where $L_o = L_c = L$ and return to a more general setup at the end of the section.

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

PROPOSITION 2. *Suppose that $L_c = L_o$. The outcome of the bargaining game is as follows. The RU and her licensee DU_i choose the mode of disclosure that maximizes their joint surplus. If $T_o > T_c$ then the RU and DU_i's payoffs are $\{F_o, T_o - F_o\}$. If $T_o \leq T_c$, then their payoffs are as follows*

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

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

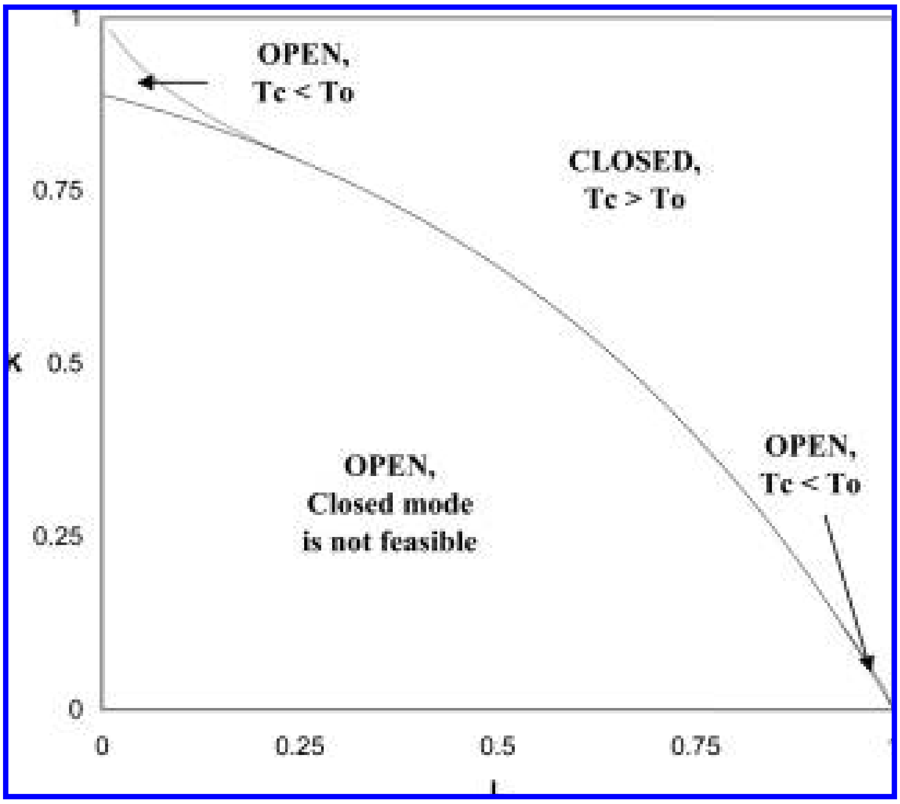

FIGURE 5. The optimal mode of licensing as a function of K and $L_o = L_c = L$. The (K, L) space is partitioned by two curves $\hat{K}(L)$ (lower line) and $K^*(L)$ (upper line). For a given L, $\hat{K}$ is the minimum level of knowledge for which the closed mode exists, K^* is the minimum level at which the closed mode dominates the open mode. The two curves coincide for all $L \in [0.25, 0.91]$.

Figure 5 presents K^* and $\hat{K}$ as functions of L. Notice that both $\hat{K}(L)$ and $K^*(L)$ decrease with L. In the areas where $K \in (\hat{K}(L), K^*(L))$, closed mode sales exist but are 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 ($K < \hat{K}(L)$).[9] This emphasizes the importance of analyzing the incentive-feasibility of the closed mode when studying the endogenous choice over licensing modes.

9. The details of the calculations that determine the properties of the two curves in Figure 5 are available upon request.

3.4. Robustness and Extensions

Opportunistic Disclosure in the Closed Mode. Our analysis is based on the assumption that trade secrets—unlike patents—do not protect the licensee from the opportunistic disclosure by the licensor to competing user of knowledge. This risk is certainly very important in the knowledge licensing environments and can hardly be mitigated by contracts where RU's fees are contingent on discovery by the other DU_j (like in Anton and Yao 1994). Such contracts are unlikely to be enforceable under standard tort law as (i) it is hard to specify the invention; and (ii) DU_j could in principle discover the idea independently of RU.

Even if these contracts were feasible, they would have only a limited impact on our results. Indeed, suppose that instead of the stake s in DU_i revenues, RU has to pay a penalty φ (e.g., to a third party) in case DU_j invents.[10] RU's wealth constraint implies $\varphi \leq F_c$, where F_c is the lump-sum fee paid by DU_i to RU. The strongest incentives are provided when $\varphi = F_c$, hence the left-hand side of the incentive compatibility constraint (6) becomes $F_c P_d$. This implies $F_c \geq (1-L_c)(1-K)/2$. Such contracts are not individually rational for DU_i whenever $K < (1-L_c)/(2-L_c)$ (for these K the DU's payoff $T_c - F_c$ is negative). Also, for $K < (1-L_c)/(13/8-L_c)$, DU_i strictly prefers the contract with positive s.

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

The less likely cases are the ones where L_c is lower or substantially higher than L_o. In the latter case there may emerge a situation where the RU's maximum payoff in the closed mode $T_c(K; L_c) - [T_o(K; L_c) - F_o(K; L_c)]$ is below her open mode fee $F_o(K; L_o)$. Expecting a low payoff in the closed mode, RU will prefer the open mode even if the joint surplus were higher in the closed mode. However, this change does not affect the "monotonicity" of the mode choice: The closed mode is still selected only for high K.[11]

10. In an unpublished appendix, we explore these issues in full detail studying arbitrary contracts contingent on $2\times2 = 4$ outcomes of discovery by each DU. It turns out that the results are very similar. Although more general contracts do reduce inefficiency because of the binding IC constraint, the equilibrium arrangements still involve a positive royalty stake $s > 0$ and have the same comparative statics properties.

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

Although the case $L_o > L_c$ is less realistic, it is also covered by our analysis. Here the DU's outside option in the closed mode is less attractive, and therefore RU expects to receive a higher payoff in the closed mode. Thus RU may want to stick to the closed mode as the open mode would only provide her with a low fee $F_o(K; L_o)$. However, if the total surplus is higher in the open mode, DU_i will pay RU for patenting (as the knowledge is not contractable, the payment should be contingent on the fact of patenting per se). A full-blown analysis—which we do not undertake in this paper—should also take into account a potential for a war of attrition between the two DUs. As both DUs benefit from switching to the open mode, each can wait for the other one to pay the RU for patenting.

Competition in the Final Product Market. We have assumed Bertrand competition between DUs in the market for the final product. This is an extreme assumption, but our results hold in other duopoly settings as long as the monopoly inventor receives a higher rent than a duopolist. In cases other than Bertrand where the duopolists obtained nontrivial rents ex post, the value of exclusive license would be lower; it would be harder to provide incentives for the RU in the closed mode. The closed mode would be less efficient and would be less likely to be chosen.

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

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 expenditure in the economy. Our model accounts for a number of countervailing effects, some of which have not been discussed before in the literature. In addition to the well-studied trade-off between incentives for the licensee and dissemination of information in the open mode, we also model the effect of leakage on the development expenditure in the closed mode and on the choice of the mode.

Our analysis of the mode choice above (Proposition 1) has straightforward implications for the comparative statics of the relative strength of these effects. Suppose that the economy is populated by RUs with high knowledge levels K (as well as of high L_o and L_c); in this case the relationship is driven by the effects in the closed mode. If the majority of RUs have less valuable ideas and the leakage is low, the open mode effects will be more important. In the intermediate cases, the relationship will be driven by the mode-switching effect.

We show that in some cases it is the latter effect that generates the $\cap$-shaped relationship between protection of intellectual property and aggregate development expenditure. To illustrate the importance of the mode-switching effect we will first analyze the impact of leakage L_o and L_c on the social welfare.

4.1. Welfare Analysis

In this section, we compare a measure of social welfare in the two modes for given parameters K, L_c, and L_o. We calculate expected social welfare as the probability of (not necessarily sole) final invention net of development costs.

PROPOSITION 3. *For all K, L_c, L_o, social welfare is always higher in the open mode rather than in the closed mode. The social welfare in the open mode,*

$$P_o(1-Q_o) + Q_o(1-P_o) + P_oQ_o - \frac{P_o^2}{2K} - \frac{Q_o^2}{2LK} = \frac{K}{2}\left(1 + \frac{L_o(1-K)^2}{1-L_oK^2}\right), \tag{15}$$

monotonically increases with both K and L_o. The social welfare in the closed mode, $P_c - P_c^2/(2K) = T_c$, monotonically increases with both K and L_c.

Proposition 3 emphasizes the importance of knowledge spillover for social welfare. First, the higher the leakage, the higher is our welfare measure in either mode. Second, the closed mode is always dominated by the open mode in terms of social welfare, even if it is less efficient from the point of view of the RU–DU$_i$ coalition. This coalition does not internalize the payoffs to the competing DU$_j$, nor to the consumers who benefit from a higher probability of invention due to the development contest between the two DUs.

Proposition 3 has straightforward normative implications. If the patent law is designed to maximize welfare, the regulators choose the highest possible L_o. As we argued above, it is difficult to raise L_o above the technologically driven leakage in the closed mode L_c; this simple result provides yet another argument in favor of the case with $L_o = L_c$.

Although Proposition 3 implies positive effect of leakage $L_{o,c}$ on welfare for a *given* mode, the relationship between leakage and welfare is not monotonic. Indeed, an increase in either L_o or L_c implies a more likely switch from the open mode to the closed mode; as, for a given K, the welfare is higher in the open mode (Proposition 3), this brings about a lower welfare. Therefore the mode-switching effect can generate $\cap$-shaped relationship between IPR protection and welfare, even though for a given mode the relationship is monotonic.

4.2. Leakage, IPR Protection, and R&D Incentives

One has to be cautious in interpreting the welfare results. Unlike development expenditures, full social returns to R&D are difficult to characterize and measure in reality; there are many more spillovers and externalities besides those described in our model. This is why empirical studies focus on the relationship between IPR protection and R&D rather than social welfare (Lerner 2001).

For simplicity, we proxy the level of IPR protection by $1 - L_o$ and the aggregate level of development expenditure by $E_1 + E_2$. 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 improves the incentives to develop for the licensee DU_i, but also weakens nonlicensee DU_j's incentives. Given K and L_o, the total development effort by DU_1 and DU_2 in the open mode is

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

PROPOSITION 4. *In the open (patent-based) mode of knowledge sales the total development effort E_o either monotonically* increases *with L_o (for $K \leq 1/3$) or has a $\cup$-shape (if $K > 1/3$). In the latter case, the minimum point of the $\cup$-shape $L_o^* = (3K - 1)K^{-2}(3 - K)^{-1}$ is an increasing function of K.*

This result is explained by the relative strength of the countervailing effects of IPR protection on licensee and nonlicensee efforts. If IPR protection is strong ($L_o = 0$), then a small decrease in it has a greater impact on DU_j than on DU_i, so the effect is more important. The positive effect on the licensee DU_i is relatively more important if K is high (and therefore the difference between K and L_oK is high). When K is low ($K < 1/3$), leakage spurs subsequent development efforts; this range of parameters corresponds to the case of early stages of new technologies such as drugs development based on new findings and techniques in biotechnology research.

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 postinvention revenues which distorts DU_i's development effort. The higher the leakage L_c, the less important this threat, hence RU's incentive constraint is satisfied through a lower revenue share s. As a result, P_c and development effort decrease as intellectual property retention $(1 - L_c)$ increases for all K for which $s^*(K; L_c)$ exists.

Finally, consider the endogenous choice of the mode of disclosure. If either L_o or L_c is sufficiently high, parties switch from open to closed mode which at the margin results in lower aggregate development expenditure. Indeed, consider the case of $L_o = L_c = L$, and $L < 0.25$ or $L > 0.91$. In this case, the switching occurs at the point where $T_c = T_o$. At this point, the total cost of development is greater in the open mode: by definition,

$$T_c = sP_c + (1-s)P_c - P_c^2/(2K) = P_c(1+s)/2 = T_o = P_o(1-\tilde{P}_o)/2.$$

Because the total effort in the closed mode $(1-s)P_c/2$ is below $P_c(1+s)/2$, it is also below $P_o(1-\tilde{P}_o)/2 + (1-P_o)\tilde{P}_o/2$ which is the total effort in the open mode.[12]

Therefore, there are four effects of stronger IPR protection in the open mode and of stronger intellectual property retention in the closed mode on the total effort by DUs:

(A) effect on the licensee's effort in the open mode (negative effect of L_o);
(B) effect on the nonlicensee's effort in the open mode (positive effect of L_o);
(C) effect on the DU's effort in the closed mode (positive effect of L_c);
(D) effect of switching from closed to open mode (negative effect of either L_o or L_c). The latter two effects are associated with the closed mode and are therefore relatively more important for higher knowledge levels K and for higher levels of knowledge leakage (L_o or L_c).

12. In the case $L \in [0.25, 0.91]$, switching occurs at $K = \hat{K}(L)$, and $T_c(\hat{K}(L); L) > T_o(\hat{K}(L); L)$, so more cumbersome calculations are required. Still, after substituting $K = \hat{K}(L)$ and $s^*(\hat{K}(L); L) = (1 + L)/4$—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 $K = \hat{K}(L)$. We need to determine the sign of $E_o - E_c$ at $K = \hat{K}(L)$, where $E_c = P_c^2/(2K) = K(1-s)^2/2$ is the development effort in the closed mode. The sign is positive whenever

$$\frac{(1 - L\hat{K}(L))^2 + L(1-\hat{K}(L))^2}{(1 - L\hat{K}^2(L))^2} > (1 - (1 + L)/4)^2.$$

The latter inequality holds. The right-hand side is below 9/16 for all $L \in [0, 1]$, and 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.

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

4.3. A Numerical Example

In this section, we illustrate the analysis above with a numerical example. To capture the mode-switching effect (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 take a family of exponential distributions on $K \in [0, 1]$:

$$g(K) = \frac{\lambda e^{-\lambda K}}{1 - e^{-\lambda}} \tag{16}$$

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 $E[K] = \int_0^1 Kg(K)dK = \lambda^{-1} - (e^{\lambda} - 1)^{-1}$.

We will consider two cases. First, we assume $L_c = L_o = L$ (see the discussion in Section 2.3) and study the effect of variation in L. Here the changes in L correspond to technologically induced variations in leakage when describing knowledge. In the second case, we will analyze the situation where much of what is codified in patents must be revealed in closed sales to convey the level of K to the buyer (as in Anton and Yao 1994). We therefore study the effect of change in L_o alone, holding L_c constant at a high level. Variations in L_o here reflect the strength of patent law and its implementation, which essentially serve to define what is considered protected.

Leakage and Development Expenditures. We first consider the case $L_o = L_c = L$. Figure 6 shows the relationship between L and the aggregate development expenditures for different values of λ, averaged out over $K \in [0, 1]$ according to the density function (16). We present the equilibrium level of investment where the

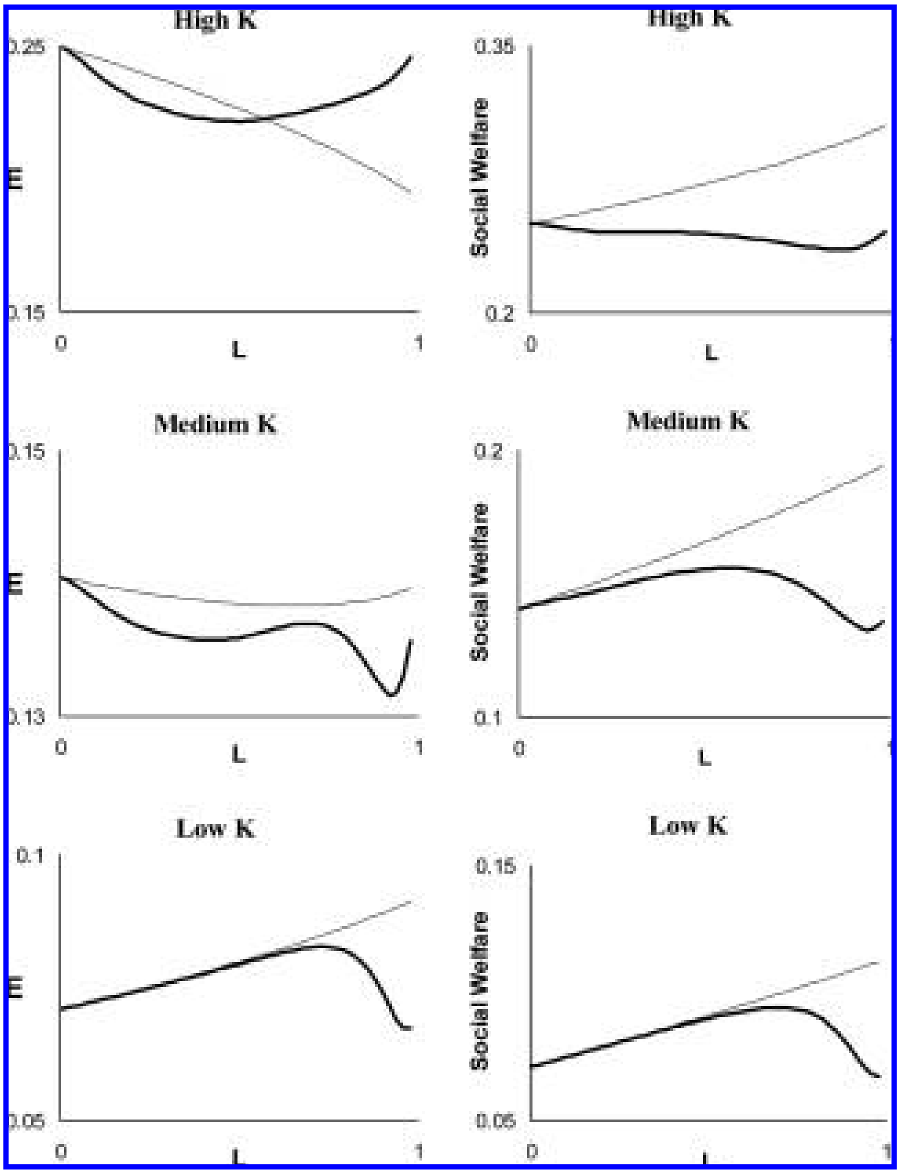

FIGURE 6. The aggregate development expenditures $E = E_1 + E_2$ and the welfare $1-(1-P_1)(1-P_2)-E$ as a function of leakage L in the case $L_o = L_c = L$. The bold line shows the relationship given the equilibrium (i.e., ex interim privately optimal) mode of disclosure. The thin line is the aggregate development expenditure in the open mode (as if the closed mode were ruled out exogenously). The three scenarios are High K ($\lambda = 0$, $E[K] = 0.5$, $g(1)/g(0) = 1$), Medium K ($\lambda = 3$, $E[K] = 0.28$, $g(1)/g(0) = 0.05$), and Low K ($\lambda = 7$, $E[K] = 0.14$, $g(1)/g(0) = 0.0009$).

mode of disclosure is chosen as described previously, that is, on the basis of higher ex interim joint surplus of the RU-cum–her licensee DU_i. 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).

The graphs show that indeed the effects (A) and (B) can only produce either a monotonic (increasing for low λ, decreasing for high λ) or a ∪-shaped relationship (for intermediate values of λ). Once we consider both modes of disclosure and allow for effects (C) and (D), the relationship between $(1 - L)$ and $[E_1 + E_2]$ changes qualitatively and does indeed become ∩-shaped for the low K and the low levels of IPR.

IPR Protection and Development Expenditures. In this section we study the effect of change in the enforcement of IPR holding the leakage from description L_c constant. We reproduce the simulations for various $L_o \leq L_c$. The results are very similar. Again, for a large range of parameters we find the ∩-shaped relationship between IPR protection and development expenditures. This relationship cannot be explained by the open-mode effects alone.

Figure 7 shows that the relationship between IPR protection $(1 - L_o)$ at $L_c = 0.9$ and the aggregate development expenditures for different values of λ is similar to the one in Figure 6.[13] The results are robust to the choice of L_c; the results for $L_o > L_c$ are also similar to the ones we present. It turns out that the most important effect behind the ∩ shape is the mode-switching effect (D): Increased leakage in either open or closed results in a higher likelihood of the closed mode.

Summary. To summarize, the shape of the relationship between $(E_1 + E_2)$ and L_o varies substantially with the ex ante distribution of knowledge K. For high λ ($\lambda \geq 7$) the relationship has a ∩ shape, but in the case of an uniform distribution ($\lambda = 0$) the relationship is actually ∪-shaped. For intermediate values of parameters ($\lambda = 3$) the graph is a superposition of a ∪ shape and ∩ 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).

Figures 6 and 7 also illustrate the impact of IPR protection on the social welfare and show that the mode-switching effect can indeed produce the ∩-shaped relationship as discussed.

13. The kinks in the Figure 7 are due to the effect described in section 3.4 which emerges when L_o is substantially below L_c.

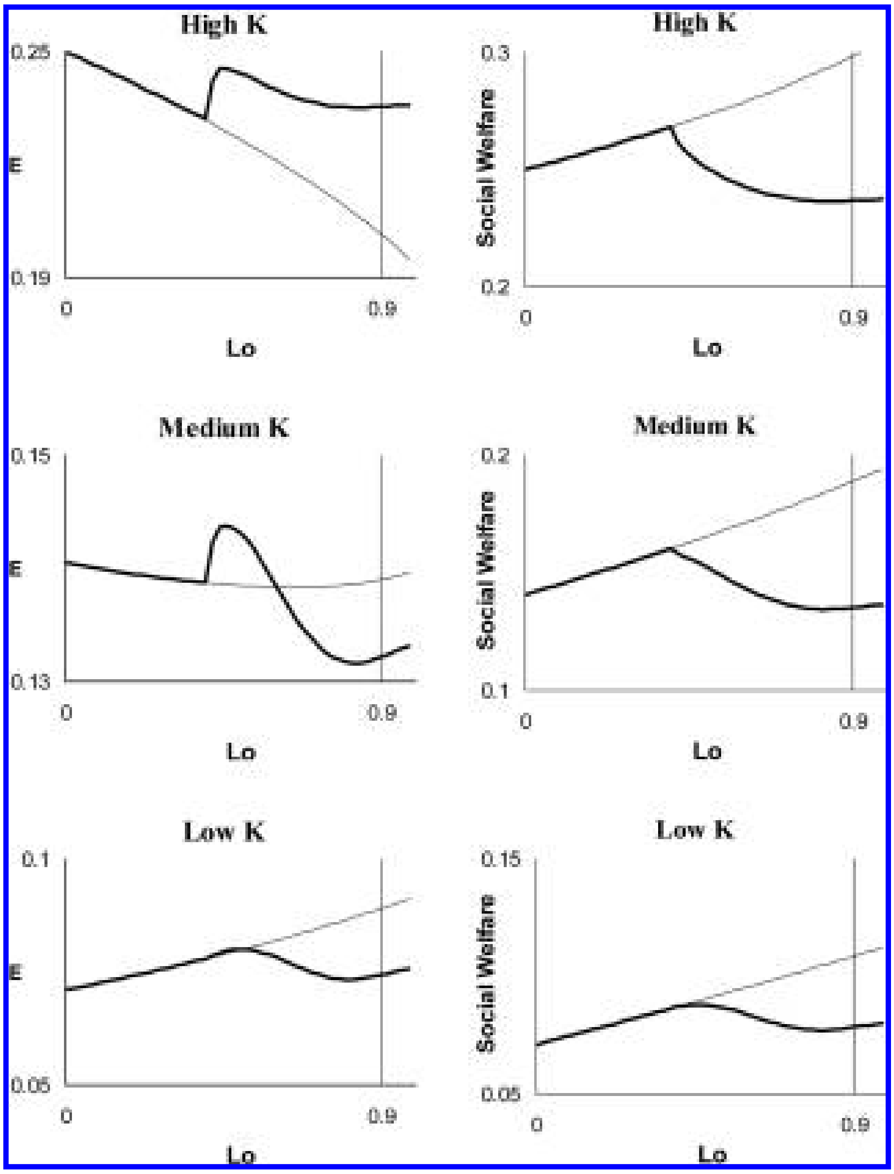

FIGURE 7. The aggregate development expenditures $E = E_1 + E_2$ and the welfare $1-(1-P_1)(1-P_2)-E$ as a function of IPR protection L_o in the case $L_c = 0.9$. The bold line shows the relationship given the equilibrium (i.e., ex interim privately optimal) mode of disclosure. The thin line is the aggregate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

5. Concluding Remarks

We develop a model of two-stage cumulative R&D. RU produces nonverifiable knowledge that has no market value per se but it can be used by DUs to create a marketable product. Because of the nonrivalrous 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 postinvention 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 postinvention 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. Our theory also generates potentially testable predictions in the structure of knowledge licensing fees in closed sales: the more valuable the knowledge, the lower the royalty stake.

Our model shows that there is no uniform ranking of the two knowledge disclosure modes in terms of overall R&D investment induced. We find that both the comparisons of magnitude of R&D 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.

Our results on the impact of IPR protection in patents on a measure of social welfare are also of considerable interest. First, we show that despite the adverse impact of low IPR protection on the development incentives of the licensee, our measure of social welfare is always decreasing in the strength of IPR. This is the case despite the dissipation of developers' rents in the event of multiple inventions by licensee and nonlicensee developers; our result is therefore different from that obtained by Bessen and Maskin (2000). Nevertheless, the existence of a trade-secret-based closed mode in our model implies that the optimal degree of IPR protection is not zero, nor even that (attainable) of the level of leakage occurring in such closed-mode negotiations prior to licensing. The reason is that weaker IPR protection in patents would lead to research units resorting to such closed-mode licensing for a greater range of knowledge levels, which in turn always harms our social welfare measure, even when the overall level of development effort (by one as opposed to two DUs) might be increased thereby. Hence, as we show, the extent of IPR protection that is optimal for social welfare may well be interior arising from endogenous choices over these two modes of knowledge licensing.[14]

Throughout our paper, we have de-emphasized the incentives of first-stage RUs to generate knowledge, and the impact of increased IPR protection thereon. In part that is because the qualitative impact of (potential) leakage on an RU's payoffs can differ substantially depending on her chosen mode of knowledge sale. The 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 a $\cap$-shaped relationship between overall R&D expenditures and the strength of IPR protection. As we have shown, such a relationship may easily result from endogenous private choices over modes of licensing of different levels of interim knowledge.[15]

Appendix: Proofs

A.1. Proof of Lemma 1

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

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

14. It might be argued that the overall optimal policy would be to set $L_o = L_c$, as it might be difficult to demand greater disclosure than this from patentees, and to ban closed-mode licensing, which is feasible in our model because such licensing entails verifiable revenue sharing across research and development units. However, regulatory prohibitions of such revenue-sharing contracts would harm social welfare in situations where revenue sharing serves to incentivize simultaneous R&D efforts by units in joint ventures, for example, as in Fulghieri and Sevilir (2004).

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

A.2. Proof of Lemma 2

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

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

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

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

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

A.3. Proof of Proposition 1

The joint surpluses in the closed and the open modes are equal to each other at $K = 1 : T_c(1; L_c) = T_o(1; L_o) = 1/2$. For any given $L > 0$ the functions $T_c(K)$ and $T_o(K)$ may cross at most once more, at $K = K^*(L_o, L_c) < 1$. At this crossing point, $T_c(K)$ grows faster than $T_o(K)$: If there is such $K^*(L_o, L_c)$ that $T_c(K^*(L_o, L_c); L_c) = T_o(K^*(L_o, L_c); L_o)$, then

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

To prove this single crossing result, we consider the ratios of joint surplus T and the "ideal" joint surplus $K/2 = \max_E[\sqrt{2KE} - E]$ in each mode (Figure 4). In the closed mode, the surplus would be $K/2$ if the opportunistic disclosure were exogenously ruled out. Straightforward calculations imply that $s^*(K, L_c)$ is a decreasing convex function of K (see [12]). Therefore the ratio $T_c/(K/2) = 1 - s^*(K, L_c)^2$ is an increasing concave function of K.

In the open mode, $K/2$ is the surplus in the absence of leakage. Hence the ratio $T_o/(K/2)$ reflects the expropriation of the joint surplus by the nonlicensee development. As discussed above, the nonlicensee DU_j's effort first increases in K, and then falls. Not surprisingly, $T_o/(K/2)$ is convex (and strictly convex for all $L_o > 0$). Indeed, $T_o/(K/2)$ is convex if $(1 - L_oK)/(1 - L_oK^2)$ is convex. But

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

is non-negative: the terms in brackets can be rearranged as

$$L_o(1 - K)^3 + (1 - L_o)(1 + L_oK^3).$$

Because $T_c/(K/2)$ is concave and $T_o/(K/2)$ is convex, and both are equal to 1 at $K = 1$, there can be three cases:

(i) $T_c/(K/2) < T_o/(K/2)$ for all $\hat{K}(L_c) \le K < 1$;
(ii) $T_c/(K/2) > T_o/(K/2)$ for all $\hat{K}(L_c) \le K < 1$;
(iii) there exists $K^* \in (\hat{K}(L_c), 1)$ such that $T_c/(K/2) < T_o/(K/2)$ for all $K \in (\hat{K}(L_c), K^*)$ and $T_c/(K/2) > T_o/(K/2)$ for all $K \in (K^*, 1)$.

The cases (ii) and (iii) are the two versions of the single crossing described in the Proposition. In order to rule out case (i), let us consider K sufficiently close to 1. If $K \to 1$, then (5) and (14) imply that

$$\begin{aligned} T_c &\to \left[K/2 - (1 - K)^2K(1 - L_c)^2/(2(1 + L_c)^2)\right],\\ T_o &\to [K/2 - (1 - K)L_o/(1 - L_o)]. \end{aligned}$$

Therefore for any $L_o > 0$, there exists a range of K sufficiently close to 1 such that $T_c > T_o$.

A.4. Proof of Proposition 3

Using (4) we find that the social welfare in the open mode,

$$\begin{aligned} &P_o(1 - Q_o) + Q_o(1 - P_o) + P_oQ_o - \frac{P_o^2}{2K} - \frac{Q_o^2}{2LK}\\ &\quad = \frac{K(1 - L_oK)^2}{2(1 - L_oK^2)^2} + \frac{L_oK(1 - K)^2}{2(1 - L_oK^2)^2} + \frac{L_oK^2(1 - L_oK)(1 - K)}{(1 - L_oK^2)^2}\\ &\quad = \frac{K}{2}\frac{(1 - L_oK)^2 + L_o(1 - K)^2 + 2L_oK(1 - L_oK)(1 - K)}{(1 - L_oK^2)^2}\\ &\quad = \frac{K}{2}\frac{(1 - L_oK^2)^2 + L_o(1 - K)^2 - L_o^2K^2(1 - K)^2}{(1 - L_oK^2)^2}\\ &\quad = \frac{K}{2}\left(1 + \frac{L_o(1 - K)^2}{1 - L_oK^2}\right), \end{aligned}$$

is always above $K/2$ and is an increasing function of L_o. Its first derivative with regard to K equals

$$\frac{(1 - L_o K)^2 + L_o(1 - K)^2}{2(1 - L_o K^2)^2}$$

and is therefore non-negative.

According to (14), the welfare in the closed mode T_c increases in K and L_c and is always below $K/2$.

A.5. Proof of Proposition 4

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

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