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

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Abstract

We develop a model of two-stage cumulative research and development (R&D), in which one Research Unit (RU) with an innovative idea bargains to license her nonverifiable interim knowledge exclusively to one of two competing Development Units (DUs) via one of two alternative modes: an Open sale after patenting this 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

Our goals in this paper are two-fold. First, we attempt to contribute to the growing literature on organization of research and development (R&D) activities within and among firms, when the potential benefits of knowledge disclosure across them is of considerable importance, but it is subject to problems of imperfect protection of the intellectual property rights assigned to (shared) interim innovative knowledge. We do so in an environment that is rich enough to capture potential competition in R&D and in bargaining over interim knowledge sales, as well as involuntary leakage or spillover of interim knowledge that is described for its potential sale. We consider both patented *open* (o-)sales and privately negotiated *closed* (c-) sales, by a first-stage research unit (RU) to one of two competing second-stage Development Units (DUs). Both these DUs have the advantage of having deep pockets, and thus of not requiring external financing for development expenditures which may lead to a successful marketable invention with some probability. In contrast, the RU with an innovative idea is assumed to have no interim wealth, and hence is better off selling her knowledge rather than trying to develop it with external financing. The rationale for this crucial assumption arises from the disincentive effects of repayments to external financiers, or revenue shares for RU knowledge licensors, on a developer's choice of effort – or other non-contractible expenditures – to combine with the acquired interim innovative knowledge to generate his probability of ultimate invention. Any probability of a loss of post-invention revenues owing to multiple inventions by both the DUs gives rise to a similar disincentive effect, on their unverifiable development efforts or expenditures.

We characterize the equilibrium and optimal choices of modes of sale or licensing of interim research knowledge, under alternative ex ante assignments of Control Rights across RU-DU pairs. These are interpreted more delicately than in the literature on Ownership or Property Rights (Hart, 1995), developed for environments lacking the excludable public good features of interim knowledge embedded in a research unit. Our notion of control pertains to (not) allowing pre-bargaining coalition formation with outside parties by agents in bilateral transactions, given wealth constraints of an agent who is either controlled by the other agent or acts independently in her ex interim interests.

Our second major goal is to use our model to explore rationales for a claimed (albeit somewhat preliminary) empirical regularity, pertaining to the relationship between the "strength of IPR protection" in a patenting system and the level of overall expenditures on R&D activities in an economy or sector. We focus on this for much of this paper in the context of ex ante independence across the RU and DUs, arising often from the unanticipated nature of many initial product ideas. 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.[1] At the same time, as Gallini (2002) notes in a literature survey, "these relationships are difficult to model and test". We develop just such a model, in which the phenomenon of licensing interim knowledge is fully accounted for. The strength of IPR protection is taken by us to be a technological parameter, arising from a leakage or spillover coefficient in the spirit of the Spence (1984) model. Such leakage of knowledge has quite dramatically different impacts on levels of development expenditures chosen by DUs who choose to engage in open versus closed sales of different levels of interim knowledge from the RU, and on the incentive-feasibility of the closed mode of sale given an RU's temptation to behave in an opportunistic fashion and sell to another DU as well. [2]

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 spillover to multiple DUs arising from the descriptions of innovations involved in the patenting process. However, patenting also serves to "facilitate a market for technological exchange" (Gallini, 2002) for exclusive licenses.[3] Important rationales for these features are articulated in Teece (2000, page 22): "Patents are in one sense the strongest form of intellectual property because they grant the ability to exclude, whereas

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[1] 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.

[2] 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.

[3] 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, in a less formal way. See also Bolton and Whinston (1993).

copyrights and trade secrets do not prevent firms that make independent but duplicative discoveries from practicing their innovations and inventions". In the context of interim (non-marketable to consumers) innovative knowledge acquired by a DU from an RU, a non-patented "exclusive" sale could thus be replicated to another DU, because he could then (if successful in his subsequent invention) pretend to have acquired interim knowledge by himself. This is especially likely to arise for interim innovative knowledge since often much of it is Tacit, being non-codifiable in a documented form; 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, applications for which now have to be in the public domain for eighteen months in USA. This same feature of "tacitness" also makes such knowledge hard to protect using IPR law (Teece, 2000), since description of its features leads to prospects of innovating around the patent, causing a partial spillover of capabilities for second-stage invention to the DUs receiving this description from an RU's patent.

To counter an RU's incentive to sell knowledge licensed in a closed sale to another DU, we allow her to receive knowledge sales proceeds partially in the form of shares in the licensee DU's post-invention revenues. The value of the RU's share must be sufficiently diminished by the RU selling her interim knowledge to the other DU so as to preclude such sales. While others such as Pisano (1989) have suggested a linkage between the co-ownership of DU equity shares and preventing opportunistic knowledge leakage, we are the first to fully analyze this mechanism and identify several novel, even surprising, features of it.[4] These include the infeasibility of designing such an incentive scheme, for sub-domains of interim knowledge levels (namely, for low levels of knowledge) which *expand* with the strength of IPR protection. We also find that RU's c-sale licensing payoffs may decrease with respect to her knowledge level. Our findings have major implications for DUs' chosen levels of development expenditures, and the chosen mode of RU's ex interim knowledge sales, including RU-DU disagreements over it which would be resolved with outcomes that depend on a DU's ex ante control (or not) over the RU.[5]

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

[5]By considering revenue rather than net profit sharing contracts between the RU and a DU, we eliminate concerns such as those raised in Anand and Galetovic (2000), of the possibility of a DU inflating his reported

Although we focus much of our analysis on ex interim interactions among an independent RU and two competing DUs, a reasonable notion of the relevance of ex ante established control rights over the RU may arise in our model, when RU is constrained by her interim wealth from making transfers to a DU. This occurs despite our maintained assumption that whether she is independent or under a DU's control, as part of a Corporate Venture for example,[6] the RU always retains the (possibly outside) option of patenting her knowledge. Thereby, she may offer an exclusive license for its full disclosure to one of the two competing DUs for a lump-sum interim fee, which results in the licensee DU obtaining the same payoff as his rival DU having the knowledge leaked via the patent. A situation may nevertheless arise in which the total net surplus across the RU and her licensee DU is greater in a closed knowledge sale than in a patent-based open sale, but the extent of the share of a DU's post-invention revenue that must be given to the RU to preclude further sale to the other DU is so high that either DU would strictly prefer the open-sale (patent-) based license, whereas RU prefers a c-sale. Note that, since even a proposed closed sale by an RU requires her to describe her interim knowledge to a DU, causing (by assumption) the same extent of knowledge leakage to him as there would be to both DUs via a patent, forcing an open sale is an option to such a DU as well, so that a DU has to obtain a weakly greater payoff in a closed sale in order to agree to licensing the RU's knowledge via this mode of sale.

Now, if an independent RU could find a coalition partner with a somewhat deeper pocket, she might be able to make an interim payment to a DU to compensate him sufficiently for the share of revenue he must give to the RU cum her partner, in order to ensure no further sale, so that he would agree to a closed sale in the scenario above. This would be the case if the RU's partner, who would obtain a part of this share to compensate her for the interim payment to the DU which she finances, can ensure that the RU would choose not to sell her interim knowledge to another DU based on their joint coalitional interest, possibly using the threat of testifying against the RU if she clandestinely tried to violate her exclusive licensing contract with the first DU. Such a financial partner, a Venture Capitalist (VC), must thus have expertise and monitoring ability in this domain, as well as reputational concerns arising from repeated partnerships of this kind. That would ensure that she would act in the interest of her coalition with the RU, which is required for the credibility of the exclusive closed sale.

While an alliance with such a VC partner aids both the wealth-constrained RU and her licensee DU (weakly) ex interim, by making possible the realization of a closed sale with

research expenditure for a given development project among its many such ventures to "hold up" an RU.

[6]There is an extensive literature on contracts between a venture capitalist (VC) and an RU in the first-stage research process, which aid the VC in controlling RU's incentives regarding shirking and inefficient continuation; see Cornelli and Yosha (2002). We analyze a different role for VC's in Section 6 below.

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higher overall (and individual) payoffs, it need not be in the ex ante interests of the DU. The reason for this is, as we show later on, that the scenario above is more likely to arise for lower levels of knowledge. Thus, it may lead to the RU preferring to generate such lower levels of interim knowledge, to sell in a closed sale in which her payoffs are decreasing in her knowledge level, rather than expending costly effort ex ante to generate higher levels of interim knowledge. Such adverse incentives for RU's knowledge generation would not arise if for low levels of her knowledge she could be forced into open patent-based sales thereof, in which she would obtain lower payoffs than in closed sales financed in part by a third-party VC partner. Ex ante DU control of an RU, whereby the DU has claims to the first offer of sale from the RU, and also veto power over any other financial partners in their joint venture, could succeed in preventing the RU from utilizing a financial partner to ensure a closed sale, for low levels of knowledge as in the scenario above. Such an ex ante RU-DU "partnership" may build in flexibility regarding open versus closed sales by giving the DU sizeable buyout options for RU's shares, while setting high prices for buy-ins by the RU to aid in closed sales in which she and her partner require a very high share. It could also penalize a potential VC partner of its RU via litigation for a "breach of contract", sufficiently so as to eliminate DU's temptation to agree to some c-sales, thus committing him not to renegotiate the terms of share sales ex interim.

Hence, a part of the predictions of our model, concerning DU-controlled corporate ventures that would "combine" research cum development, would be that such an institution would on average generate more promising interim knowledge, enough to compensate the DU for his cost of forming such a venture, including those of compensating "his" RU for her lower revenue for low levels of knowledge, and for her effort costs of generating greater knowledge with higher probabilities. As a part of this process, or for those knowledge levels at which both prefer an open sale or when a closed sale is (incentive-) infeasible, we would expect to see buyouts of any ex ante RU-share in the joint venture by the DU, which is very common in such equity-based ventures. Somewhat surprisingly, our rationale would also predict that such corporate ventures would be more likely to patent their interim knowledge than the independent RUs cum their VC partners, rather than transferring such knowledge via closed sales in revenue-sharing partnerships in the development phase of their innovations.[7]

In this paper, we develop the full analysis of our model, utilizing a simple algebraic

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[7]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.

example in which interim knowledge and development "effort" combine multiplicatively via a Cobb-Douglas function with equal weights to generate the probability of a final successful development. Both DUs choose their effort taking into account (a) any sharing of their ex post revenue with the RU, and (b) the knowledge level of the rival DU from any leakage via a patent or as a licensee. Such a rival's knowledge level would in turn affect his effort choice, and hence the prospects for multiple second-stage inventions, which would dissipate the rents of either inventor. These determine their incentives to incur effort (cum non-contractible development expenditures) in a Nash equilibrium. We proceed by first considering the impact of knowledge leakage to the non-licensee DU in open sales, and of the sharing of revenue with the RU in closed sales, on the total net surplus of the combination of the RU and her licensee DU in these two modes of sale. We then characterize the division of these surpluses across the RU and her licensee DU, utilizing the major lessons of noncooperative bargaining theory beginning with Stahl (1977) and Rubinstein (1982).[8] Finally, we examine the impact of RU's interim wealth constraint on this division, and the chosen mode of knowledge sale, under varying assumptions regarding her independence.

2 Related literature

To place our model in the context of related literature, we now proceed to delineate several key facets of its ongoing development, without trying to be exhaustive in its description, before continuing to develop the salient features of our model. 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. Such endogenous disclosure, which serves as a signal of ultimate invention prospects to investors, was assumed to be non-contractible for licensing to other DUs. In later work, Bhattacharya and Chiesa (1995) considered a more symmetric environment with two such RU cum DU firms which need

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[8]All the bargaining among the RU and the two DUs in our model is carried out under complete information, since we assume that a description of the knowledge K (that leads to leakage of capability LK to its receiver, $L \leq 1$) suffices to establish its level, determining the maximum probability of second stage invention it could lead to. For a model of bargaining over knowledge licenses under incomplete information about the licensors' knowledge level across two RU cum DUs, in which a large portion of the first-best Pareto frontier across them is attainable without any delays, see the recent paper of d'Aspremont, Bhattacharya, and Gerard-Varet (2000).

external finance, that may be provided by a common financier (or a capital market) or by separate financiers. They showed that if a common financier learns enough about these firms' interim knowledge, he may for some parameters wish to transfer knowledge from one of these to the other, which both of these firms would prefer ex ante provided that it still leaves them sufficient incentives to do costly first-stage research. Bessen and Maskin (2000) have also arrived at a similar result in the context of the desirability of (no) patent protection in cumulative R&D, assuming no overall rent dissipation in the event of joint inventions, whereas Llobet, Hopenheyn and Mitchell (2000) have analyzed a compulsory licensing scheme for the transfer of patent rights to later sole inventors in a stationary Markovian environment.

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. However, they did not analyze the possibility of the RU making such a second (clandestine) sale to another DU in equilibrium, after her first sale. We extend their analysis by explicitly modelling RU's incentives to make such a sale in a setting where the spillover of knowledge from its description is partial. We describe a structure of knowledge licensing fees that may overcome RU's 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" or non-contractible inputs, so that she is better off selling her knowledge exclusively to one of the two competing DUs.[9] There may also be other, technological advantages of DUs over the RU in undertaking development, e.g. sunk costs of shared facilities for development of similar products. Notice that the fact that each DU develops multiple products (invented by different RUs) naturally reinforces our assumption of non-verifiable development effort.

The impact of knowledge licensing fees that are contingent on the licensee DUs' post-invention revenue on their 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 scope of patents,

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[9]Anton and Yao (2002) also retain this assumption, in a paper combining a signalling role for prior free disclosure as in Bhattacharya and Ritter (1983) with the sale of non-verifiable interim knowledge backed by warranties, or reversed payments from the RU to her exclusive licensee DU if he fails to finally invent.

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). 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.[10] In our work, we follow Hart (1995) who assumes absolute inalienability of human capital.[11] 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 definition 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.

Subsequent authors, such as 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

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[10]The RU'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).

[11]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 we rule out in our model!

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).[12]

The rest of the paper is organized as follows. In Section 3, we set up our model, describing its timing and notation, and provide a preview of some of our results later. In Section 4 we characterize the equilibrium mode of disclosure. In Section 5 we study the relationship between IPR protection and overall R&D activity, aggregated over varying levels of interim knowledge. In Section 6 we consider the role of RU's interim financial constraints, and provide a rationale for corporate venturing by a DU. Section 7 concludes.

3   The model

3.1   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 6, 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 RU's effort e. The c.d.f. of knowledge

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[12]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).

$G(K; e)$ is decreasing in effort e. For each DU, his probability P of successful development is a function of his acquired knowledge and subsequent development effort $E \in [0, 1/2]$: [13]

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

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.

The timing of events is as follows:

Ex ante. RU undertakes effort e.

Ex interim. The RU and the DU(s) to which she makes a licensing offer, with a description of knowledge, infer the level of knowledge K produced in the research stage. The exact *content* of RU's knowledge is not observed by either DU and requires further disclosure. The parties, RU and DU(s), choose the mode of disclosure and bargain about the licensing fee. Their bargaining proceeds as an alternating offer game with an outside option of registering IPR (open mode). Once a patent is registered, there is no return to the closed mode. 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.[14] 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 bargaining game is similar to the one in Bolton and Whinston (1993). RU and the DUs bargain about disclosure of full 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. $DU_{1,2}$ then choose their post-licensing levels of development effort (equivalently, their probabilities of successful development). We will denote $P_i = P_o$ as the probability of development for the firm that acquires full knowledge K, and $P_j = Q_o$ as the probability of development for the firm that develops on the basis of leaked knowledge LK. These are chosen as Nash equilibrium strategies in the game between the two DUs, in which the payoff of $V = 1$ arises ex post only for a DU which invents alone.

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[13] 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.

[14] 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.

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 lump-sum transfer from DU_i to RU as well as about RU's share s (e.g. via royalties) in DU_i's post invention 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 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 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 Q_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, which is also their payoff if neither invents.

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.

We assume that courts can observe and verify ex post revenues but not the interim knowledge K, or the "effort" expenditures e and $E_{i,j}$. We also 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 $Z(P_i, P_j; K)$ the expected ex interim payoff of this DU in the development race where the other DU_j chooses probability of invention P_j. According to (1), DU_i's effort cost is $E_i = P_i^2/(2K)$ so that in the open mode of knowledge sale:

$$Z_o(P_i, P_j; K) = [(1 - P_j)P_i - P_i^2/(2K) - F_o] \tag{2}$$

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

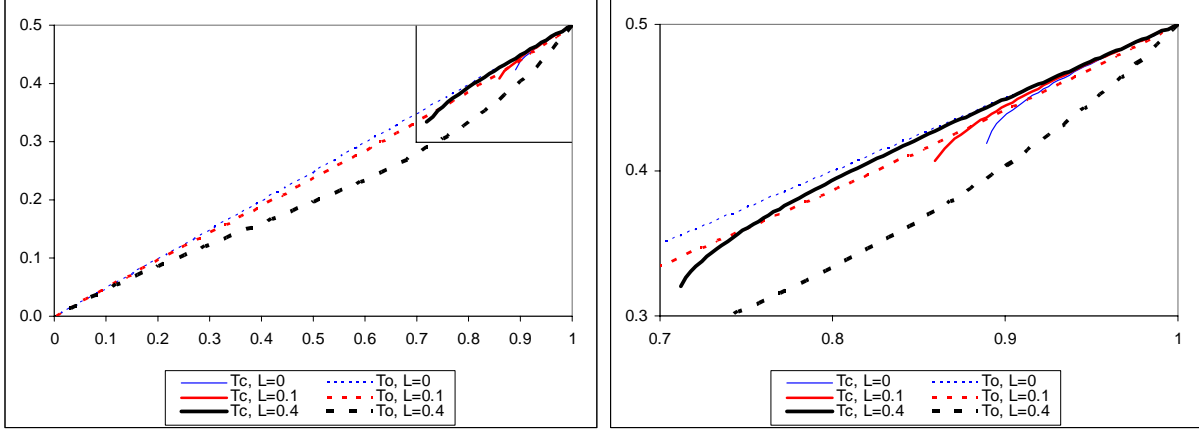Correspondingly, in the closed model of knowledge sale:

Figure 1: 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 is a closeup for $K \in [0.7, 1]$.

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

where P_c is the optimal choice of P_i in this mode. Again, the cash payment $\{F_c - sP_c\}$ is made before the choice of development effort, so DU_i chooses $P_i = K(1-s)$ to maximize (3).

3.2 Preview of some results

We find that, except in situations where the required revenue share of the RU in a closed sale is very high, the ordering of T_c versus T_o determines the chosen mode of sale. This ordering depends crucially on the level of the knowledge leakage parameter L, as well as on the level of the interim knowledge itself. Depending on this parameter, the curve $T_c(K; L)$, as a function of interim knowledge level K, may lie everywhere below or above the $T_o(K; L)$ curve, or cross it once from below. However, as we have noted above, the $T_c(K; L)$ curve may not exist – closed sales may not be incentive-feasible – for knowledge levels K below a certain level. This non-existence region is larger when the leakage/spillover coefficient L is smaller, as depicted in Figure 1.

We also find that the impact of smaller leakage or higher IPR protection on $T_c(K, L)$ and $T_o(K, L)$ are very different; $T_c(K, L)$ is everywhere increasing in L for all K, whereas the impact of increasing L on $T_o(K, L)$ goes in the exact opposite direction. To evaluate the impact of changing L on overall development activity, one must also take into account the

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impact of increasing L on the probability of successful sole second stage development by non-licensees in open sales, who gain from knowledge spillover via patenting. This mode is chosen in the subset of interim knowledge levels K for which the closed mode either does not exist or is dominated by the open mode $T_o(K, L) > T_c(K, L)$. Thus, it is quite a complex task to evaluate the impact of changing L on the overall probability of induced interim development expenditures, for a given cross-sectional or cross-sectoral distribution of interim knowledge levels K, and also of L itself perhaps.[15]

We accomplish this task, so as to investigate the conditions for an inverted U-shaped relationship between the strength of IPR protection, parameterized as $(1-L)$, and the levels of and invention prospects arising from overall R&D (here just development) expenditures. In our model, the fact that $T_c(K, L)$ either decreases or may fail to exist for a larger range of K when $(1 - L)$ rises, is an important source of the potential non-monotonicity of the impact of IPR protection on overall development efforts cum prospects. The forces giving rise to these results arise from economic effects which transcend the specifics of the algebraic cum numerical example we use to demonstrate these, as we argue below while discussing the economic intuition behind our main results.

4   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 two modes of disclosure. Then we study the outcome of bargaining and describe the division of this surplus between RU and DU_i.

4.1   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 race. The joint surplus of RU and DU_i will therefore equal $T_o = [Z_o + F_o]$; see (2). The competing DU_j will use

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[15] As L decreases, the potential reward to the RU from a clandestine second sale after a closed "exclusive" sale increases, so that her temptation has to be countered (if it is feasible) by an increased revenue share in her original licensee DU. This diminishes this DU's incentive for expending non-contractible inputs to enhance his probability of successful second-stage development of RU's interim knowledge. In contrast, in an open sale decreased L reduces the non-licensee's chosen "effort", in turn improving the licensee's incentive to expend effort. The implications for the probabilities of sole invention, which determine DUs' chosen research expenditures, summed over both DUs is ambiguous, and depend on the levels of K and L.

the leaked knowledge LK, and will therefore receive $[(1 - P_o)Q_o - Q_o^2/(2LK)]$. Here the probabilities P_o, Q_o satisfy the Nash equilibrium conditions:

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

$$Q_o = \arg\max_q \left[(1 - P_o)q - q^2/(2LK) \right] = LK(1 - P_o)$$

Straightforward calculations yield:

$$P_o = \frac{K - LK^2}{1 - LK^2}; \quad Q_o = \frac{LK - LK^2}{1 - LK^2}. \tag{4}$$

Note that P_o is increasing in K for all L, while Q_o is initially increasing and then decreasing in K, approaching the limit of $Q_o = 0$ as $K \to 1$ for all $L < 1$.

The fee F_0 is determined as the outcome of the alternating offer bargaining game described in the Section 3.1.

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 $Z_o = [(1 - P_o)Q_o - Q_o^2/(2LK)]$, whereas RU obtains $F_o = [\{P_o(1 - Q_o) - P_o^2/(2K)\} - \{(1 - P_o)Q_o - Q_o^2/(2LK)\}]$ 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 Z_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 (4) we obtain the equilibrium payoffs of the RU and DU:

$$T_o = \frac{K(1 - LK)^2}{2(1 - LK^2)^2}; \quad F_o = \frac{K(1 - L)}{2(1 - LK^2)}; \quad Z_o = T_o - F_o = \frac{K(1 - K)^2 L}{2(1 - LK^2)^2}. \tag{5}$$

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 Z_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 Z_o is first increasing and then decreasing in K, approaching zero as $K \longrightarrow 1$ for all $L < 1$.

4.2   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:

$$sP_c - sP_c(1 - P_d) \geq \left((1 - P_c)P_d - P_d^2/(2K)\right) - \left((1 - P_c)Q_d - Q_d^2/(2LK)\right) . \quad (6)$$

The left-hand side in (6) is the reduction in the RU's share in DU_i's revenue 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 payoffs, and thus reduces the value of RU's stake from sP_c to $sP_c(1 - P_d)$ as described in (6).

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

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

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

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

In equilibrium, RU and DU_i will choose the minimum possible $s \in [0, 1]$ that satisfies (6). Cancelling the sP_c terms on in the left hand side of (6) and using (7) and (8), we rewrite the incentive constraint as $sP_cP_d \geq [K(1 - P_c)^2/2 - LK(1 - P_c)^2/2]$. By substituting from (9) into (6), we obtain

$$sK(1 - s) \geq (1 - K(1 - s)) (1 - L)/2; \quad (10)$$

or, for all $K > 0$

$$2s^2 - (1 + L)s + (1 - L)(1/K - 1)] \leq 0 \quad (11)$$

Since the parties are interested in finding the lowest s that still satisfies (6), we need to solve for the smaller root of the quadratic equation obtained by setting (11) 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:*

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

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

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

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 (6)) increase in s so rapidly that the benefits of keeping DU_i a monopoly (the left-hand side in (6)) never catch up with it. Since $P_c = K(1 - s)$, sP_c reaches its maximum at $s = 1/2$, implying $s^*(K; L) \leq 1/2$.

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. Nevertheless, the value of RU's stake in post-invention revenues sP_c *decreases* in K. Indeed, whenever $s = s^*(K; L)$ exists, $s = s^*(K; L)$ decreases in K, and so that right-hand side of (10) 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

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

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 more sustainable when the leakage is high; indeed, RU's payoff from a deviant second sale declines when L increases, so that $\widehat{K}(L)$ 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.

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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 results in a higher joint surplus T_c. 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.

4.3 Ex interim optimal mode of disclosure

The parties choose the mode that maximizes the ex interim joint surplus of RU and her licensee DU.[16] 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 IPR are protected well (L is low) then 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 equal 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 (5) and (14) 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.

It turns out that for any given L the functions $T_c(K)$ and $T_o(K)$ cross at most once. As fine-grid numerical calculations show, for any $K < 1$

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

There can be three cases (Figure 1). *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 $L \in [0.25, 0.91]$.[17] 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

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[16]Until Section 6 we ignore RU's ex interim financial constraints.

[17]We need to evaluate the sign of $T_c(K; L) - T_o(K; L)$ at $K = \widehat{K}(L)$. Substituting (13) into (12) and (14), and using (5) we find that this expression is positive whenever $D(L) = 1 - (1 + L)^2/16 - (1 - L\widehat{K}(L))^2/(1 -$

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:

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 2 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 closed mode dominates the open mode ($K > K^*(L)$) or where closed mode is not incentive-feasible ($K < \widehat{K}(L)$). This emphasizes the importance of studying alternative modes of disclosure and especially the analysis of incentive-feasibility of the closed mode.

4.4 Ex interim bargaining in the closed mode

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. We ignore RU's interim wealth constraint.

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

$L\widehat{K}^2(L))^2$ 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 $L_2 = 0.91$.
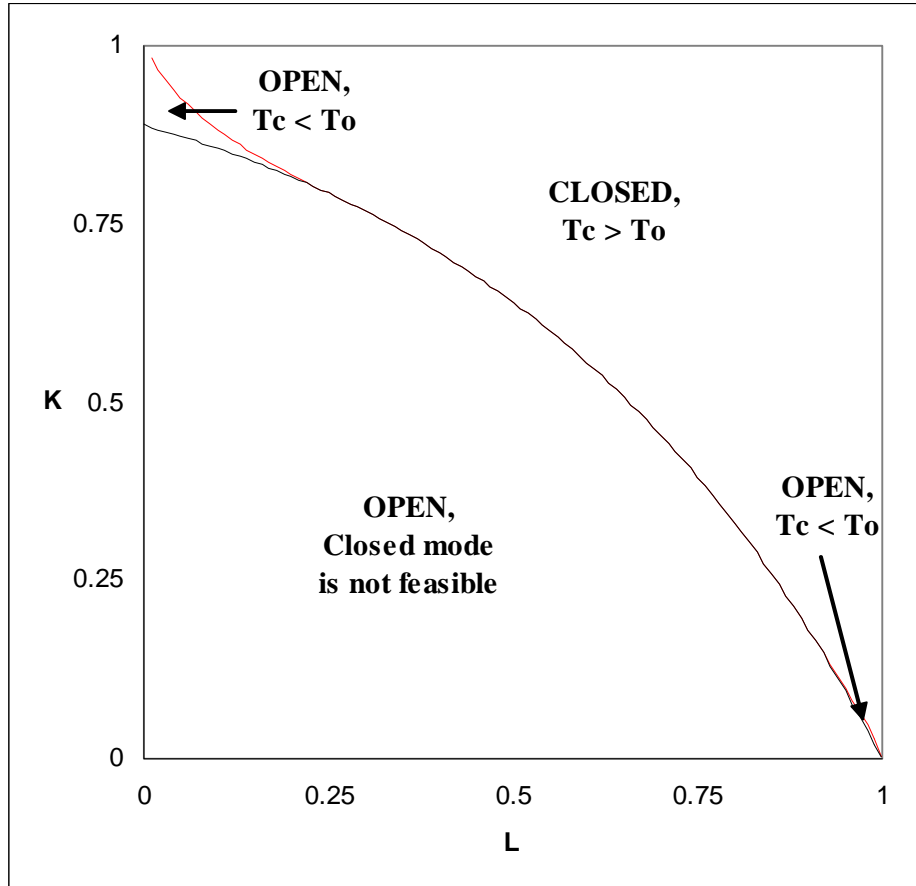
Figure 2: The optimal mode of disclosure (in CAPS) as a function of K and L. The (K, L) space is partitioned by two curves $\widehat{K}(L)$ (lower line) and $K^*(L)$ (upper line). For a given L, $\widehat{K}$ is the minimum level of knowledge for which the closed mode exists, K^* is the minimum level at which the closed mode dominates the open mode. The two curves coincide for all $L \in [0.25, 0.91]$.

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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*

$$
\begin{aligned}
\left\{ \tfrac{T_c}{2},\ \tfrac{T_c}{2} \right\} && if \quad \tfrac{T_c}{2} \geq F_o \ and \ \tfrac{T_c}{2} \geq T_o - F_o \\
\{F_o,\ T_c - F_o\} && if \quad \tfrac{T_c}{2} < F_o \\
\{T_c - T_o + F_o,\ T_o - F_o\} && if \quad \tfrac{T_c}{2} < T_o - F_o
\end{aligned}
$$

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.[18]

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 6.

5 IPR protection and the level of R&D expenditures

In this Section we study the relationship between IPR protection proxied by $(1 - L)$ 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.

We first consider the role of IPR protection given the 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, the total development effort by DU_1 and DU_2 in the open mode is

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

Lemma 4 *In our 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*

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[18] 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.

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.[19]

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, $T_c = sP_c + (1-s)P_c - P_c^2/(2K) = P_c(1+s)/2 = T_o = P_o(1-Q_o)/2$. Since the total effort in the closed mode $(1-s)P_c/2$ is below $P_c(1+s)/2$, it is also below $P_o(1-Q_o)/2 + (1-P_o)Q_o/2$ 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 closed mode also reduces total effort, at the level of knowledge $K = \widehat{K}(L)$.[20] 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*

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[19]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 $L = \Lambda(K)$.

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

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 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 the "inverted U-shape" relationship cannot be produced by the effects (A) and (B) alone. Once the closed mode is introduced, so 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)). Below we consider a numerical example where introduction of the closed mode can indeed produce an inverted U-shape relationship between IPR strength and the aggregate 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 $K \in [0, 1]$:

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

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

Figure 3 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 (15). We present the equilibrium level of investment where the mode of disclosure is chosen as described above, i.e., on the basis of higher ex interim joint surplus of the RU cum her licensee DU_i. In order to understand the incremental importance of the effects (C) and (D), we also plot the total development expenditures, summed across DU_1 and DU_2, in the open mode (as if the closed mode were exogenously ruled out).

Let us first consider the effect of IPR protection on the licensed and non-licensed DUs' development expenditures in the open mode. As shown in Figure 3, the effects (A) and
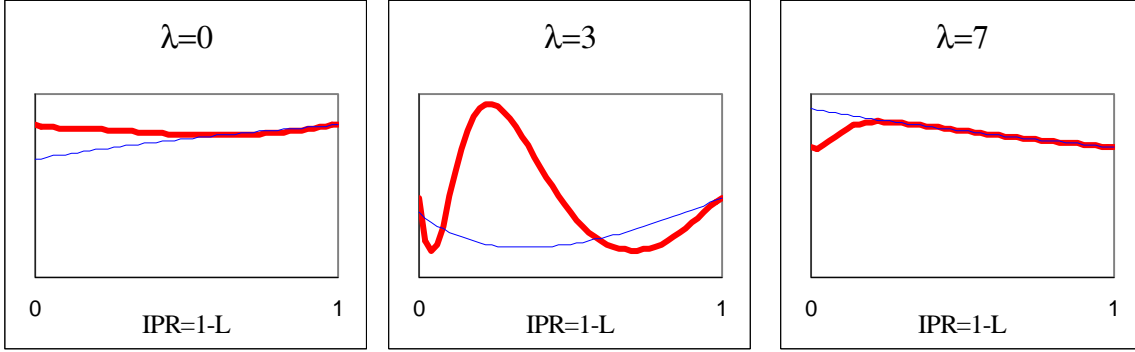
Figure 3: The thick line shows the aggregate development expenditures $E_1 + E_2$ as a function of IPR protection $(1 - L)$ given the equilibrium (i.e. ex interim privately optimal) mode of disclosure. The thin line is the aggregate development expenditure in the open mode (as if the closed mode were 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 $\lambda = 7$ ($\mathsf{E}K = 0.14$, $g(1)/g(0) = 0.0009$).

(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).[21]

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.

Total development expenditures can be higher with the closed mode when the latter

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[21] As discussed above, for a given K effects (A) and (B) produce either decreasing or U-shaped relationship. However, when K is high the minimum point of the U-shape of E_o with regard to $(1 - L)$ is so close to $1 - L = 0$ that the relationship is an increasing one for most of parameter values. Once we average out over K, we obtain an increasing function when λ is low and therefore high levels of K are more likely.

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).

6 Corporate venturing 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.[22] 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

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[22]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 prohibiteve costs of financing independent development by RU: the investment in development may be much larger than I.

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$_i$.[23]

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, 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

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[23]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. 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.

	$K = K^L$	$K = K^H$
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

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*

$$\max\{T_c^H/2, F_o^H\} - e < s^L P_c^L - I^L \text{ and}$$
$$\max\{T_c^H/2, F_o^H\} - e > F_o^L. \tag{16}$$

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

$$(T_c^H - e) - T_c^L > 0. \tag{17}$$

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 (16) 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 (16) and (17) 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.

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 $sP_c > \max\{F_o, T_c/2\}$.

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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.

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-rival 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 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.

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 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. Also, the impact of ex ante research effort on the distribution of interim knowledge levels serves to determine whether corporate venturing improves welfare or not.

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. 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 6 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.

Our model may also be extended to analyze employment relationship in research-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.

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