Licensing interim R&D knowledge*

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Abstract

This paper considers three firms that engage in an R&D contest to develop a new commercial technology. For a broad range of parameters, the firm that leads the contest (i.e., has the highest probability of success) is better-off licensing or selling its superior interim knowledge to one or both of the two lagging firms rather than holding on to its lead. Although transferring interim R&D knowledge to the lagging firms erodes the technological lead of the leading firm, it allows it to extract rents from its rivals and can possibly create value by increasing the chance that the licensee(s) will develop the new technology when the leading firm fails.

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1 Introduction

Many licensing agreements are reached at the early stages of the R&D process before the commercial success of the licensed technology has been guaranteed. Such agreements seem to be particularly common in the chemical and pharmaceutical industries where they account for over 20% of all licensing agreements (Anand and Khanna, 2000). This percentage is even higher in biotechnology. Kalamas, Pinkus, and Sachs (2002) report that about a third of all licensing deals between the top 12 pharmaceutical companies and biotechnology firms from 1991 to 2002 took place during the preclinical testing stage.[1] Howard (2004) reports that there is an increasing trend towards early-stage licensing in biotechnologly, with over 60% of all agreements between the top 20 pharmaceutical firms and biotechnology firms from 1997 to 2002 taking place at the discovery and the lead molecule phases, which are the earliest stages in the development process of new drugs. Moreover, over 50% of all biotechnology licensing agreements studied by Lim and Veugelers (2003) were made at very early stages of their development, before any prototypes or clinical test results were available.[2] By contrast, less than 5% of the agreements in their data were at advanced stages of development. Bearing in mind that the success rate for new drugs at the preclinical testing stage is only about 20% for self-originating drugs and about $25\% - 38\%$ for acquired new drugs (see e.g., DeMasi, 2001), it is clear that early-stage licensing agreements involve interim R&D knowledge that may or may not eventually lead to a commercially successful product or process.

Despite the prevalence of early-stage technology licensing, most of the licensing literature, with only few exceptions, has studied licensing of commercial products or processes.

[1] The developement of new drugs consists of several, mostly sequential, phases: the discovery phase in which the targeted substance is identified and validated with a medically important function, the lead molecule phase in which the lead molecule that is supposed to interact with the targeted substance is identified and validated, the preclinical phase in which the drug is tested on animals or in vitro, the phase I, phase II, and phase III clinical trails in which the new compound is tested on human subjects, and the New Drug Application (NDA) stage in which the company files an NDA with the Food and Drug Administration (FDA). For some drugs, the FDA requires additional studies (Phase IV) to evaluate long-term effects. In total, the entire development process takes on average $10 - 12$ years.

[2] Their data consists of over 240 U.S. biotechnology licensing contracts, dealing mainly with the health care industry, and include diagnostics, drugs, cultivation of cells, and laser imaging.

This paper by contrast examines licensing of precommercial interim R&D knowledge which enhances the chances to develop a commercially profitable technology but does not guarantee it. The difference between commercial and precommercial technologies is important because in my model, firms have no incentives to either license or sell commercial technologies due to the resulting competition in the product market. However, as we shall see, for a broad range of parameters, firms do have an incentive to license or to sell interim R&D knowledge.

Specifically, I consider an R&D contest between three firms for developing a new technology (e.g., a new drug, a superior production process). The R&D outcome is binary: each firm either succeeds to develop the new technology or it fails. The paper focuses on the licensing decisions of the three firms at some interim stage, before the R&D contest has yet been decided. The main question then is whether the leading firm (the one with the best chances to develop the new technology) will prefer to hold on to its technological lead or whether it would prefer to license out its superior knowledge to one of the lagging firms (and if so to whom) or to both lagging firms.

The decision to license interim R&D knowledge is driven in my model by the interplay between three effects. First, licensing interim R&D knowledge raises the probability that the licensee will successfully develop the new technology when the leading firm fails. This effects creates value which the leading firm can capture through a license fee. Second, the agreement raises the probability that the licensee will successfully develop the new technology when the leading firm also succeeds. This effect destroys value since competition between firms in the product market lowers their profits. Third, a licensing agreement lowers the probability that a non-licensee will be the sole developer of the new technology. Consequently, the lagging firms are willing to pay the leading firm not only for the right to obtain its superior knowledge but also in order to ensure that the remaining firm does not obtain it.[3]

Given these three effects, I completely characterize the optimal licensing decision of the leading firm. In Section 3, I show that the leading firm will prefer to license out its

[3] This effect is reminiscent of Katz and Shapiro (1986) where a licensor plays the potential licensees off against one another so in equilibrium, the licensees are made worse off due to the innovation. This idea was also used by Anton and Yao (1994, 2002) to show that an independent inventor can extract rents from an exclusive buyer of his knowledge by threating to reveal the knowledge to a rival and thereby destroy the buyer's monopoly rents.

interim knowledge either to both lagging firms or exclusively to the second firm in the R&D contest, provided that its chances to develop the new technology are not too high. Licensing is not profitable when the leading firm's chances to develop the new technology are high because then it is highly likely that both the leading firm and its licensee(s) will end up developing the new technology and will compete against each other in the product market. Paradoxically then, a license of interim knowledge is valuable only if the licensor has a limited amount of R&D knowledge to transfer. It is also interesting to note that the leading firm never licenses its interim knowledge to the weakest rival - this will compromise the leading firm's own chance to be the sole developer of the new technology by too much as it will convert a weak rival into an equally strong one.

In Section 4, I examine how the equilibrium changes under various scenarios. In Section 4.1, I consider the case where it is feasible for the leading firm to transfer only parts of its interim knowledge to the lagging firms. I show that whenever the leading firm is sufficiently close to success, it will prefer to issue vacuous licences to both lagging firms that transfer them as little knowledge as possible. The lagging firms accept these vacuous licenses because of the leading firm's threat that if one of them rejects its offer it will transfer its knowledge exclusively to the remaining firm. In Section 4.2, I show that the two lagging firms can improve their bargaining position vis-a-vis the leading firm by reaching a bilateral licensing agreement which transfers the knowledge of the second firm in the contest to the third firm. In Section 4.3, I consider the case where the leading firm's knowledge is more valuable to the lagging firms. This situation is interesting because there are many cases in which relatively small innovative firms license their precommercial technologies to large firms that have better capabilities to commercialize these technologies. I show that in this case, the leading firm will licenses its interim knowledge for a broader range of parameters than in Section 3. In Section 4.4, I turn to the possibility that under licensing, the success probabilities of the licensor and the licensees become positively correlated. I show that the qualitative results of Section 3 remain valid when the degree of correlation is small, but not otherwise. In particular, for moderate levels of correlation, the leading firm may prefer to issue an exclusive license to the weakest rival. And, in Section 4.5, I show that a ban on exclusive licenses will induce the leading firm to issue nonexclusive licenses to both lagging firms only if its knowledge ensures a relatively low probability of success. Otherwise, such a ban will have the unintended consequence of inducing the leading firm to hold on to its technological lead rather than license it out.

In Section 5, I examine the possibility that the leading firm will sell rather than license its superior interim knowledge. The difference is that under licensing, the leading firm stays in the contest, whereas under selling it exits the contest after transferring its interim knowledge. As might be expected, selling knowledge is particularly valuable when it ensures a high probability of success: given that the leading firm exits the contest, the acquirer is left with a high probability of being the sole developer of the new technology. Moreover, each of the two lagging firms is eager in this case to ensure that the leading firm does not sell its knowledge exclusively to the rival firm. Selling knowledge, however, is not always profitable: when the leading firm's knowledge is only associated with an intermediate probability of success, the leading firm is better off holding on to its technological lead.

Finally, in Section 6, I relax the assumption that the interim knowledge of the three firms can be Blackwell ordered (i.e., the knowledge of the last firm is a subset of the knowledge of the second firm, which is in turn a subset of the knowledge of the leading firm), and assume instead that each firm has its own unique approach to R&D. In that case, the knowledge of each firm is valuable to both of its rivals. I show that in this case, the joint expected payoff of the three firms may be maximized when one of the lagging firms is the licensor, and moreover, it may be profitable for the three firms to engage in cross-licensing agreements.

There is a sizeable literature on the licensing of commercial technologies (see Kamien, 1992, for a survey). Most of this literature considers an outside inventor (say an R&D lab) who holds a patent for a commercially profitable technology and asks what is the most profitable way for the inventor to license his technology to firms that are active in the market. By contrast, the licensor in my paper is an active firm who engages in an R&D contest with its licensees for developing a commercially profitable technology. Licensing to rivals or potential rivals has also been studied by Gallini (1984) and Rockett (1990). Gallini shows that a firm might license its technology to a potential rival in order to lower its incentive to invent a superior technology. In Rockett (1990), the licensor is an incumbent firm who licenses its technology to a weak entrant in order to deter entry by a stronger entrant. In both papers however, licensing involves commercial technologies and its main motivation is to preserve the dominant position of the licensor. In my model by contrast, licensing involves interim R&D knowledge and while it compromises the licensor's chances to be the sole developer of the new technology, it also allows it to extract rents from the licensees.

There are already few papers that also consider licensing of interim R&D knowledge, but their focus is very different than mine. Bhattacharya, Glazer, and Sappington (1992) study the conditions under which simple licensing schemes induce the members of a research joint venture to optimally invest in R&D and fully disclose their private interim R&D knowledge to other members. d'Aspremont, Bhattacharya, and Gerard-Varet (2000) consider two rivals in a winners-takes-all R&D contest that bargain over the licensing of interim R&D knowledge from the leading to the lagging firm under the assumption that the leading firm has private information about the extent of its technological lead. Since there are only two firms in their model, there is no rent extraction effect (the licensor plays the licensees off against each other) which plays a major role in my analysis, and moreover, it is impossible to examine the difference between exclusive and non exclusive licensing agreements which is one of the main issues that I look at. Finally, Bhattacharya and Guriev (2006) consider a research lab that licenses its interim R&D knowledge to one of two competing firms that can commercialize this knowledge. They compare cases where the research lab can commit to sell its knowledge to only one firm and cases where it cannot. Unlike in my paper, the licensor is an outsider who cannot commercialize the interim R&D knowledge on its own.

2 The model

Three firms engage in a contest to develop a new commercial technology (e.g., a new drug, a superior production process). Suppose that the contest has reached some intermediate stage at which the knowledge that three firms have already accumulated can be summarized by a vector $(\lambda_1, \lambda_2, \lambda_3)$, where $\lambda_i < 1$ represents the probability that firm i will eventually succeed to develop the new technology. With probability $1 - \lambda_i$, firm i will fail and will develop nothing. I assume without a loss of generality that $\lambda_1 > \lambda_2 \geq \lambda_3$, so that firm 1 is the current leader in the contest, with firm 2 being second and firm 3 being last.

In what follows, I will assume that the probabilities λ_1, λ_2, and λ_3, are independent of each other and are common knowledge.[4] Moreover, I will assume that the knowledge of the three firms can be Blackwell ordered: firm 3's knowledge is a subset of 2's knowledge, which is in turn a subset of firm 1's knowledge. This assumption implies that firm 1 may wish to license its superior knowledge either to firm 2, or to firm 3, or to both. If it does, the probability that the licensee(s) will successfully develop the new technology jumps to λ_1, although it remains independent of the success probability of firm 1.

In Sections 4.1-4.4 below I will relax some of these assumptions: I will consider the possibility of a partial transfer of knowledge in Section 4.1, the possibility that firm 2 will license its knowledge to firm 3 before both firms are approached by firm 1 in Section 4.2, the case where firm 1's knowledge is more valuable to firms 2 and 3 than it is to firm 1 in Section 4.3, and positive correlation between the success probabilities of firm 1 and its licensee(s) in Section 4.4.

Given the model's basic setup, a licensing agreement creates three main effects. First, it creates value by raising the probability that the licensee will successfully develop the new technology when firm 1 fails. Second, a licensing agreement raises the probability that the licensee will successfully develop the new technology when firm 1 also succeeds. This effect destroys value since the aggregate profits are higher when only one firm succeeds to develop the new technology. Third, a licensing agreement lowers the probability that a non-licensee will be the sole developer of the new technology. This effect allows firm 1 to extract rents from its licensees by "threatening" them that should they reject its offer, it will license out its technology exclusively to the rival firm.

For simplicity, I assume that once the R&D contest ends (and each firm either succeeds or fails to develop the new technology), the three firms engage in Bertrand competition in

[4] The assumption that the vector $(\lambda_1, \lambda_2, \lambda_3)$ is common knowledge is clearly made for simplicity. However, given that very little is known about the licensing of interim R&D knowledge, this assumption seems like a natural starting point. Moreover, in many applications, this assumption is a reasonable approximation since firms can assess each others' probability of success through various channels, like patent applications, results of clinical trails, public announcement, scientific publications, informal exchange of information between employees of different firms, etc.

the product market. If more than one firm succeeds to develops the new technology (whether this technology leads to a new product or to marginal cost reduction), then competition in the product market drives the profits of all firms to 0. Likewise, profits are driven to 0 when all firms fail to develop the new technology. By contrast, if only one firm is successful, then this firm monopolizes the product market and earns a profit that I normalize to 1. This modelling approach allows me to study the three effects of licensing in as simple manner as possible. It should be noted though that the same three effects will also be present under alternative models of product market competition, albeit in a less extreme manner.[5] Another advantage of this modelling approach is that it creates a stark difference between interim R&D knowledge and commercial technologies: with Bertrand competition, firms never wish to license commercial technologies because their resulting profits in the product market are 0. Moreover, there are also no gains from selling commercial technologies because the technology is worth the same to the licensee and the licensor. Therefore the incentive to license or sell R&D knowledge arises in my model precisely because the knowledge is interim and is not associated with a commercial technology.

3 Exclusive and nonexclusive licenses

Absent licensing, each firm i earns a monopoly profit (normalized to 1) only if it succeeds to develop the new technology while its two rivals fail. Hence, its expected payoff is given by:

$$\pi_i(n,n) = \lambda_i(1-\lambda_j)(1-\lambda_k), \qquad i \neq j,k, \tag{1}$$

where (n,n) indicates that firm 1 did not license its knowledge to neither firm 2 not firm 3.

If firm 1 decides to license out its knowledge, it can either issue an exclusive license to only one rival or issue nonexclusive licenses to both rivals.[6] In both cases, the licensees

[5] A general model of product market competition is considerably more complicated because each firm will have 6 possible payoffs associated with the following cases: (i) the firm succeeds while its two rivals fail, (ii) the firm and one other rival succeed, (iii) all three firms succeed, (iv) the firm and one rival fail while the other rival succeeds, (v) the firm fails while its two rivals succeed, and (vi) all three firms fail. Under Bertrand competition, each firm has only 2 possible payoffs: 1 in case (i) and 0 otherwise.

[6] When firm 1 issues an exclusive license to firm $j = 2,3$, it commits not to transfer its knowledge to firm $k \neq j$. Firm j on its part, also commits not to transfer the licensed knowledge to firm k.

fully obtain firm 1's knowledge and hence their probability of success jumps to λ_1.[7] In order to find out whether firm 1 will issue licenses and whether these licenses will be exclusive or nonexclusive, suppose that at the beginning of the licensing stage, firm 1 can make a pair of take-it-or-leave-it offers to firms 2 and 3 at fees T_2 and T_3, respectively. If firms 2 and 3 reject, then none of them gets a license and no payments are made. If only one firm accepts firm 1's offer, then this firm obtains an exclusive license and pays the associated fee to firm 1. The rejecting firm pays nothing and does not get access to firm 1's knowledge. If both firms accept, then a tie-breaking rule determines whether firm 2 gets an exclusive license, or firm 3 gets an exclusive license, or both firms get licenses. The precise type of the tie-breaking rule is chosen by firm 1 along with the fees T_2 and T_3 and will be specified in Lemma 1 below.

If firm 1 licenses its knowledge exclusively to firm 2 for a license fee T_2, then the expected payoffs of the three firms are given by:

$$\pi_1(y,n) = \lambda_1(1-\lambda_1)(1-\lambda_3) + T_2, \tag{2}$$

$$\pi_2(y,n) = \lambda_1(1-\lambda_1)(1-\lambda_3) - T_2, \tag{3}$$

and

$$\pi_3(y,n) = \lambda_3(1-\lambda_1)^2. \tag{4}$$

Apart from T_2, these equations differ from equation (1) in that firm 2's probability of success is now λ_1 instead of λ_2. The expected payoffs of the three firms are completely analogous when firm 1 licenses its knowledge exclusively to firm 3 instead of firm 2.

If firm 1 issues nonexclusive licenses to both firms 2 and 3, then the expected payoffs of the three firms become:

$$\pi_1(y,y) = \lambda_1(1-\lambda_1)^2 + T_2 + T_3, \tag{5}$$

and

$$\pi_j(y,y) = \lambda_1(1-\lambda_1)^2 - T_j, \qquad j = 2,3. \tag{6}$$

[7]In other words, I implicitly assume that firm 1 cannot divide its knowledge and transfer only parts of it to its licensees. In Section 4.1, I relax this assumption.

That is, both firms 2 and 3 pay fees to firm 1 and all three firms have the same probability, λ_1, of developing the new technology.

Lemma 1: *Suppose that firm 1 wishes to issue an exclusive license to firm $j = 2, 3$. Then, the optimal scheme from its perspective is to make take-it-or-leave-it offers with*

$$T_j^* = (1 - \lambda_1)\left(\lambda_1(1 - \lambda_k) - \lambda_j(1 - \lambda_1)\right), \qquad k \neq j,$$

and

$$T_k^* = 0,$$

and set a tie-breaking rule that specifies that only firm j gets a license if both firms accept their respective offers. If firm 1 wishes to issue nonexclusive licenses to both firms 2 and 3, then the optimal scheme from its perspective is to set

$$\widehat{T}_j^* = (\lambda_1 - \lambda_j)(1 - \lambda_1)^2, \qquad j = 2, 3,$$

and set a tie-breaking rule that specifies that both firms get licenses if both accept their respective offers.

Proof: First, suppose that firm 1 wishes to issue an exclusive license to firm 2, and suppose that it makes simultaneous take-it-or-leave-it offers to firms 2 and 3 with licensing fees T_2^* and T_3^* and a tie-breaking rule that specifies that firm 2 will receive an exclusive license if both firms accept their respective offers. Since $T_3^* = 0$, firm 3 will surely accept. Now, T_2^* specified in the Lemma is the solution of $\pi_2(y, n) = \pi_2(n, y)$, where $\pi_2(n, y)$ is firm 2's payoff when firm 3 gets an exclusive license. Therefore firm 2 will also accept.[8] Given that both firms accept, the tie-breaking rule determines that firm 2 will receive an exclusive license. Similar arguments apply when firm 1 wishes to issue an exclusive license to firm 3.

Next, suppose that firm 1 wishes to issue nonexclusive licenses to firms 2 and 3 and makes them simultaneous take-it-or-leave-it offers with licensing fees $\widehat{T}_2^*$ and $\widehat{T}_3^*$ and a tie-breaking rule that specifies that both firms receive a license if both accept their respective

[8] Of course, firm 1 can always lower T_2^* slighty to ensure that firm 2 strictly prefers accepting over rejecting. Since this point is trivial, I will not mention it in the sequel.

offers. Since $\widehat{T}_2^*$ and $\widehat{T}_3^*$ specified in the lemma are the solutions of $\pi_2(y,y) = \pi_2(n,y)$ and $\pi_3(y,y) = \pi_3(y,n)$, it is clear that (accept, accept) is once again a Nash equilibrium.

Finally, note that the licensing fees stated in the lemma are the highest that firms 2 and 3 will agree to pay since they represent the difference between a firm's expected payoff when it gets a license (the "best" outcome the firm can hope for) and its expected payoff when the rival firm gets an exclusive license (the "worst" outcome from the firm's perspective). ■

Lemma 1 shows that whenever firm 1 wants to issue licenses, it can make take-it-or-leave-it offers to firms 2 and 3 which both firms accept. The tie-breaking rule then specifies which firm gets a license. The optimal licensing fees are designed such that firm 1 extracts not only the entire surplus that the licensees receive from using firm 1's knowledge, but also the surplus from preventing the rival firm from using this knowledge exclusively. In a sense then, firm 1 plays firms 2 and 3 off against one another in the sense that if one of them rejects its respective offer, firm 1 issues an exclusive license to the remaining firm. This situation is of course the worst case scenario for firms 2 and 3 because it means that they are left behind in the R&D contest. Hence, the licensing fees can be viewed as reflecting a payment not only for firm 1's knowledge, but also for preventing the rival firm from being the exclusive licensee of this knowledge.

When firm 1 issues licenses it has to trade off the fees that it receives against the erosion in its chance to be the sole developer of the new technology. The next proposition studies this trade-off and fully characterizes firm 1's licensing decisions.

Proposition 1: *In equilibrium, firm* 1 *will*

(i) *issue nonexclusive licenses to both firms* 2 *and* 3 *if* $\lambda_1 < 1/3$*;*

(ii) *issue an exclusive license to firm* 2 *if* $1/3 \leq \lambda_1 < \lambda_1^*$*, where* $\lambda_1^* \in \left(\frac{1}{2-\lambda_3}, 1\right)$ *is defined implicitly by*

$$\begin{aligned} B(\lambda_1, \lambda_2, \lambda_3) &\equiv \pi_1^*(y,n) - \pi_1(n,n) \qquad (7) \\ &= \lambda_1 (1-\lambda_3)(1-2\lambda_1+\lambda_2) - \lambda_2 (1-\lambda_1)^2 = 0, \end{aligned}$$

and is increasing with λ_2 *and decreasing with* λ_3*; and*

(iii) *not issue any licenses if* $\lambda_1 \geq \lambda_1^*$.

Proof: If firm 1 issues an exclusive license to firm 2 at T_2^*, then its expected payoff is

$$\begin{aligned} \pi_1^*(y,n) &= \lambda_1(1-\lambda_1)(1-\lambda_3) + T_2^* \\ &= (1-\lambda_1)\left[2\lambda_1(1-\lambda_3) - \lambda_2(1-\lambda_1)\right]. \end{aligned} \tag{8}$$

If firm 1 issues an exclusive license to firm 3 at T_3^*, then its expected payoff is

$$\begin{aligned} \pi_1^*(n,y) &= \lambda_1(1-\lambda_2)(1-\lambda_1) + T_3^* \\ &= (1-\lambda_1)\left[2\lambda_1(1-\lambda_2) - \lambda_3(1-\lambda_1)\right]. \end{aligned} \tag{9}$$

If firm 1 issues nonexclusive licenses at $\widehat{T}_2^*$ and $\widehat{T}_3^*$, then its expected payoff is

$$\begin{aligned} \pi_1^*(y,y) &= \lambda_1(1-\lambda_1)^2 + \widehat{T}_2^* + \widehat{T}_3^* \\ &= (1-\lambda_1)^2\left[3\lambda_1 - \lambda_2 - \lambda_3\right]. \end{aligned} \tag{10}$$

And, if firm 1 does not issue any licenses, then its expected payoff is given by (1).

Comparing equations (8)-(10) reveals that since $\lambda_1 > \lambda_2 \geq \lambda_3$, then $\pi_1^*(y,y) > \max\{\pi_1^*(y,n), \pi_1^*(n,y)\}$ for all $\lambda_1 < 1/3$, and $\pi_1^*(y,n) > \max\{\pi_1^*(y,y), \pi_1^*(n,y)\}$ for all $1/3 < \lambda_1 < 1$. That is, if firm 1 wishes to issue licenses at all, it will issue nonexclusive licenses to both firms 2 and 3 if $\lambda_1 < 1/3$ and will issue an exclusive license to firm 2 if $1/3 < \lambda_1 < 1$.

To examine whether firm 1 will issue licenses at all, suppose that $\lambda_1 < 1/3$. In that case, if firm 1 issues licenses at all, it will issue nonexclusive licenses to both firms 2 and 3. Using equations (10) and (1) yields,

$$\begin{aligned} \pi_1^*(y,y) - \pi_1(n,n) &= (1-\lambda_1)^2\left[3\lambda_1 - \lambda_2 - \lambda_3\right] - \lambda_1(1-\lambda_2)(1-\lambda_3) \\ &= (2\lambda_1 - \lambda_2 - \lambda_3)(1 - 3\lambda_1 + \lambda_1^2) + \lambda_1(\lambda_1^2 - \lambda_2\lambda_3) > 0, \end{aligned} \tag{11}$$

where the inequality follows because $1/3 > \lambda_1 > \lambda_2 \geq \lambda_3$. Hence, whenever $\lambda_1 < 1/3$, firm 1 is better off issuing nonexclusive licenses than not issuing any licenses.

Next, suppose that $\lambda_1 \geq 1/3$. Then, if firm 1 issues licenses at all, it will issue an exclusive license to firm 2. The difference between the expected payoff of firm 1 when it issues an exclusive license to firm 2 and when it issues no licenses is given by $B(\lambda_1, \lambda_2, \lambda_3)$, which is defined in the proposition. Note that $B(\lambda_1, \lambda_2, \lambda_3)$ is concave in λ_1 and that evaluated at $\lambda_1 = 1/3$,

$$B(\frac{1}{3}, \lambda_2, \lambda_3) = \frac{(1-\lambda_2)(1-\lambda_3) - 4\lambda_2\lambda_3}{9} > 0, \tag{12}$$

where the inequality follows because, given that $1/3 = \lambda_1 > \lambda_2 \geq \lambda_3$, the first term in the numerator is bounded from below by 4/9, whereas the second term is bounded from above by 4/9. On the other hand, as λ_1 approaches 1,

$$\lim_{\lambda_1 \longrightarrow 1} B(\lambda_1, \lambda_2, \lambda_3) = -(1-\lambda_2)(1-\lambda_3) < 0. \tag{13}$$

Since $B(\lambda_1, \lambda_2, \lambda_3)$ is an inverse U-shaped function of λ_1, (12) and (13) ensure the existence of a unique value of λ_1, denoted λ_1^*, such that $B(\lambda_1, \lambda_2, \lambda_3) > 0$ for all $1/3 < \lambda_1 < \lambda_1^*$ and $B(\lambda_1, \lambda_2, \lambda_3) < 0$ for all $\lambda_1^* < \lambda_1 < 1$. The value of λ_1^* is implicitly defined by $B(\lambda_1, \lambda_2, \lambda_3) = 0$. Notice for later use that evaluated at λ_1^*, $B(\lambda_1, \lambda_2, \lambda_3)$ is decreasing with λ_1. Also, notice that evaluated at $\lambda_1 = \frac{1}{2-\lambda_3}$,

$$B\left(\frac{1}{2-\lambda_3}, \lambda_2, \lambda_3\right) = \frac{(1-\lambda_3)(\lambda_2-\lambda_3)}{(2-\lambda_3)^2} > 0.$$

Hence, $\lambda_1^* > \frac{1}{2-\lambda_3}$.

To examine how λ_1^* varies with λ_2 and λ_3, note that $\frac{\partial \lambda_1^*}{\partial \lambda_j} = -\frac{\frac{\partial B(\lambda_1^*, \lambda_2, \lambda_3)}{\partial \lambda_2}}{\frac{\partial B(\lambda_1^*, \lambda_2, \lambda_3)}{\partial \lambda_1}}$, $j = 2, 3$. Since evaluated at λ_1^*, $B(\lambda_1, \lambda_2, \lambda_3)$ is decreasing with λ_1, it follows that $\frac{\partial \lambda_1^*}{\partial \lambda_j} = sign\left[\frac{\partial B(\lambda_1^*, \lambda_2, \lambda_3)}{\partial \lambda_2}\right]$, $j = 2, 3$. The result follows by noting that

$$\begin{aligned} \frac{\partial B(\lambda_1^*, \lambda_2, \lambda_3)}{\partial \lambda_2} &= \lambda_1^*(1-\lambda_3) - (1-\lambda_1^*)^2 \\ &= \frac{\lambda_1^*(1-\lambda_3)}{\lambda_2}[\lambda_2 - (1 - 2\lambda_1^* + \lambda_2)] \\ &= \frac{\lambda_1^*(1-\lambda_3)}{\lambda_2}[2\lambda_1^* - 1] > 0, \end{aligned}$$

where the second equality follows by substituting for $(1-\lambda_1^*)^2$ from (7) and the inequality follows since $\lambda_1^* > 1/2$. Likewise,

$$\frac{\partial B(\lambda_1^*, \lambda_2, \lambda_3)}{\partial \lambda_3} = -\lambda_1^*(1 - 2\lambda_1^* + \lambda_2) = -\frac{\lambda_2(1-\lambda_1^*)^2}{1-\lambda_3} < 0,$$

where the second equality follows by substituting for $(1 - 2\lambda_1^* + \lambda_2)$ from (7). ■

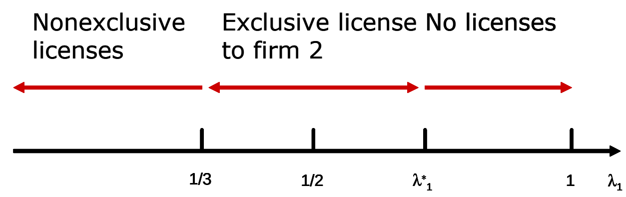

Figure 1: Exclusive and nonexclusive licensing of interim R&D knowledge

Proposition 1 is illustrated in Figure 1. When λ_1 is close to 1, firm 1 is better off holding on to its technological lead and not issuing any licenses. Intuitively, λ_1 close to 1 means that it is highly likely that once firm 1 licenses out its knowledge, more than one firm will end up developing the new technology and competition in the product market will drive profits to 0. Consequently, licenses are not worth much to firms 2 and 3 but they entails a large loss of technological lead from firm 1's point of view.

By contrast, when λ_1 is intermediate (between 1/3 and λ_1^*), firm 1 prefers to issue an exclusive license to its closest rival, firm 2. Although Lemma 1 shows that firm 3 is willing to pay more than firm 2 for an exclusive license when $\lambda_1 < 1/2$, licensing knowledge exclusively to firm 2 rather than to firm 3 also implies a smaller erosion of firm 1's technological lead, because then firm 1's faces a weak non-licensee (firm 3), rather than a strong one (firm 2). Notice that since λ_1^* is increasing with λ_2 and decreasing with λ_3, the range of parameters for which firm 1 will issue an exclusive license to firm 2 (of which λ_1^* is the upper bound) expand as firms 2 becomes a stronger competitor and as firm 3 becomes a weaker competitor.

When $\lambda_1 < 1/3$, firm 1 is better off licensing its knowledge to both firms 2 and 3. Now, firm 1's chance to develop the new technology is relatively small, so licensing involves only a small loss of technological advantage. Although the licensing fees that firms 2 and 3 are willing to pay in this case to ensure that they are not left behind in the R&D contest are also small, they are sufficiently large to more than compensate firm 1 for this loss.

Finally, note that Proposition 1 implies that firm 1 never wishes to issue an exclusive license to firm 3 which is the "weak" rival in the sense that it is lagging behind firms 1 and 2 in the R&D contest. Such an option is dominated by issuing nonexclusive licenses to firms 2 and 3 when $\lambda_1 < 1/3$ and by issuing an exclusive license to the "strong" rival, firm 2, when

$\lambda_1 > 1/3$.[9]

4 Extensions

4.1 Partial transfer of knowledge

Thus far I have assumed that when firm 1 licenses its knowledge to firms 2 and 3, it transfers it fully. The question is what happens when firm 1 can transfer only parts of its superior knowledge: will it have an incentive to transfer only limited amounts of its knowledge or transfer all of it?

To examine this question, suppose that firm 1 can control how much of its superior knowledge it transfers to firms 2 and 3, and let $\Delta_2 \leq \lambda_1 - \lambda_2$ and $\Delta_3 \leq \lambda_1 - \lambda_3$ be the amounts of interim knowledge transferred to firms 2 and 3. Moreover, suppose that as before, firm 1 can make take-it-or-leave-it offers to firms 2 and 3, which, are designed such that if a firm rejects its respective offer, then firm 1 will transfer its entire knowledge to the rival firm.[10] The resulting expected payoff of firm 1, as a function of Δ_2 and Δ_3, is given by

$$\begin{aligned}\pi_1(\Delta_2, \Delta_3) &= \lambda_1(1-\lambda_2-\Delta_2)(1-\lambda_3-\Delta_3) \\ &+ \left[(\lambda_2+\Delta_2)(1-\lambda_1)(1-\lambda_3-\Delta_3) - \lambda_2(1-\lambda_1)^2\right] \\ &+ \left[(\lambda_3+\Delta_3)(1-\lambda_1)(1-\lambda_2-\Delta_2) - \lambda_3(1-\lambda_1)^2\right].\end{aligned} \tag{14}$$

Since $\pi_1(\Delta_2, \Delta_3)$ is a linear function of Δ_2 and Δ_3, there are 4 possibilities in equilibrium: (i) $\Delta_2 = \lambda_1 - \lambda_2$ and $\Delta_3 = \lambda_1 - \lambda_3$ (firm 1 transfers its entire knowledge to both firms), (ii) $\Delta_2 = \lambda_1 - \lambda_2$ and $\Delta_3 = 0$ (firm 1 transfers its entire knowledge exclusively to firm 2),

[9] This result stands in contrast to Rockett (1990), where the dominant firm prefers to license out its technology to a "weak" rival in order deter entry by a "strong" rival. The difference arises because the motivation for licensing in Rockett's paper is to preserve the licensor's dominant position, whereas in my paper, the main motivation is to increase the overall probability of success and extract rents from the licensees.

[10] To illustrate, suppose that firm 1 wishes to issue an exclusive license to firm 2. Firm 1 can then offer firms 2 and 3 to obtain Δ_2 and $\Delta_3 = \lambda_1 - \lambda_3$ at fees T_2 and T_3, such that firm i's expected payoff if it accepts is equal to its payoff if it rejects the offer and firm j recieves an exclusive license. In addition, firm 1 sets a tie-breaking rule that stipulates that when both firms accept, firm 2 receives an exclusive license.

(iii) $\Delta_2 = 0$ and $\Delta_3 = \lambda_1 - \lambda_3$ (firm 1 transfers its entire knowledge exclusively to firm 3), or (iv) $\Delta_2 = \Delta_3 = 0$ (firm 1 transfers none of its knowledge). It is easy to check that in the latter case, $\pi_1(0,0) > \pi_1(n,n)$: if firm 1 prefers to transfer none of its knowledge, then it will issue firms 2 and 3 vacuous licenses that transfer them virtually no knowledge rather than not issue any licenses. Firms 2 and 3 will accept these vacuous licenses because of firm 1's "threat" that if its offer is rejected, it will transfer its entire knowledge to the rival firm. Essentially then, firm 1 extracts rents from firms 2 and 3 in exchange for its guarantee not to transfer its entire knowledge exclusively to the rival firm.

I now establish the following result:

Proposition 2: *Suppose that firm 1 can transfer partial amounts of knowledge to firms 2 and 3. Then in equilibrium, firm 1 will*

(i) *issue nonexclusive licenses to firms 2 and 3 and transfer them its entire knowledge if* $\lambda_1 \leq 1/3$*;*

(ii) *issue an exclusive license to firm 2 and transfer it its entire knowledge if* $1/3 < \lambda_1 < \frac{1-2\lambda_3}{2-3\lambda_3}$*, where* $\frac{1-2\lambda_3}{2-3\lambda_3} \leq 1/2$*;*

(iii) *issue nonexclusive vacuous licenses to firms 2 and 3 which transfer them as little knowledge as possible if* $\lambda_1 \geq \frac{1-2\lambda_3}{2-3\lambda_3}$.

Proof: See the Appendix.

As Figure 2 shows, firm 1's ability to license partial knowledge matters only when $\lambda_1 \geq \frac{1-2\lambda_3}{2-3\lambda_3}$. In this range, firm 1 is issuing nonexclusive "vacuous" licenses to firms 2 and 3 and transfers them virtually no knowledge rather than issuing an exclusive license to firm 2 or not issuing licenses at all. As argued above, firms 2 and 3 accept the vacuous licenses because they wish to ensure that firm 1 will not transfer its entire knowledge exclusively to the rival firm. A similar scheme was ruled out in Section 3 by the implicit assumption that firm 1 can either transfer all of its interim knowledge to its licensees or none of it.

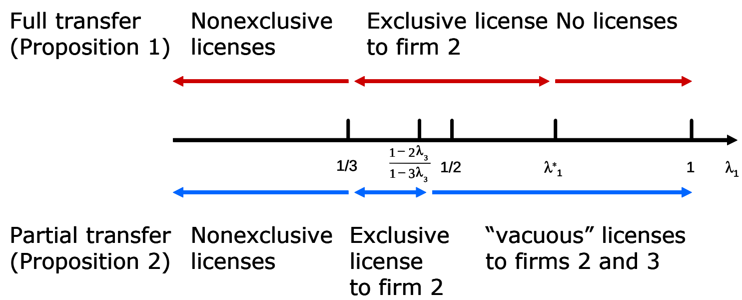

Figure 2: Partial transfers of interim R&D knowledge

One may wonder why firm 1 does not wish to sign similar vacuous agreements in which it transfers no knowledge to its rivals when $\lambda_1 < \frac{1-2\lambda_3}{2-3\lambda_3}$. After all, such agreements allow firm 1 to extract rents from its rivals without compromising its technological lead. However, while transferring knowledge raises the probability of a tie between firm 1 and its licensees, it also raises the probability that the licensees will successfully develop the new technology when firm 1 fails. Hence, transferring knowledge has the potential of creating value which firm 1 can capture through the license fees. This value-creating effect is particularly large when λ_1 is small, because then the probability of a tie is small.

4.2 Transfer of interim knowledge between firms 2 and 3

The fact that firm 1 plays firms 2 and 3 off against one another when it makes them take-it-or-leave-it offers, suggests that firms 2 and 3 may wish to engage in a bilateral licensing agreement before either one of them is approached by firm 1. According to the agreement, firm 2 will transfer its knowledge to firm 3. This agreement can then favorably affect the terms of the licensing agreements that firm 1 will eventually offer firms 2 and 3.

To explore this possibility, suppose that firms 2 and 3 expect that firm 1 will offer them licenses, and recall from Lemma 1 that firm 1 sets its licensing fees such that the expected payoffs of firms 2 and 3 under both exclusive and nonexclusive licenses will be equal to their respective expected payoffs when firm 1 issues an exclusive license to the rival firm. These expected payoffs are equal to $\lambda_2(1-\lambda_1)^2$ and $\lambda_3(1-\lambda_1)^2$, respectively. Since the joint expected payoff of firms 2 and 3, $(\lambda_2+\lambda_3)(1-\lambda_1)^2$, increases with λ_3, it is clear that the two firms benefit from transferring firm 2's knowledge to firm 3 and thereby raising λ_3 to λ_2. As Proposition 1 shows, such an agreement does not affect firm 1's choice between exclusive and nonexclusive licenses since this choice depends only on whether λ_1 is above or below 1/3. On the other hand, since λ_1^* decreases with λ_3, the agreement between firms 2 and 3 narrows the range of λ_1 for which firm 1 issues an exclusive license to firm 2.

Even when firm 2 and 3 do not expect that firm 1 will offer them licenses, i.e., whenever $\lambda_1 > \lambda_1^*$, they can still benefit from reaching a licensing agreement provided that $\lambda_2 < 1/2$. Such an agreement raises their joint expected payoff from $(1-\lambda_1)(\lambda_2(1-\lambda_3)+\lambda_3(1-\lambda_2))$ to $2\lambda_2(1-\lambda_2)(1-\lambda_1)$. The reason why λ_2 needs to be below 1/2 for such an agreement to be jointly profitable is that it must raise firm 3's chances to be the sole developer of the new technology by more than it lowers firm 2's chance.

Proposition 3: *Suppose that firms 2 and 3 expect that firm 1 will issue licenses (either exclusive or nonexclusive). Then, they will benefit from licensing firm 2's knowledge to firm 3 before they are approached by firm 1. This agreement will narrow the set of parameters for which firm 1 issues an exclusive license to firm 2. If firms 2 and 3 expect that firm 1 will not issue any licenses, then they still benefit from a licensing agreement between themselves provided that $\lambda_2 < 1/2$.*

4.3 Firm 1's knowledge is worth more to firms 2 and 3

There are many cases in which relatively small firms license out their interim R&D knowledge to large corporations. This situation is quite common for example in the software industry or in biotechnology.[11] An important feature of such agreements is that the licensees have more resources and better capabilities to successfully develop and commercialize the licensed technology. Consequently, the R&D knowledge is more "valuable" to the licensee than it is to the licensor. A natural question then is how would firm 1's incentive to license its technology change when its knowledge is worth more to firms 2 and 3. This question is addressed in the next proposition.

[11] For an excellent source on biotechnology licensing agreements (many of which are between small biotechnology firms and large pharmaceutical firms), see http://www.jameshatton.com/public/

Proposition 4: *Suppose that when firm 1's knowledge is λ_1, firm 1's probability of developing the new technology is merely $\phi\lambda_1$, where $\phi \in [0,1]$. That is, whenever $\phi < 1$, firm 1's technology is worth more to firms 2 and 3 than to firm 1. Then, in equilibrium, firm 1 will*

(i) *issue nonexclusive licenses to both firms 2 and 3 if $\lambda_1 < \lambda_1(\phi) \equiv \frac{1+\phi-\sqrt{1-\phi+\phi^2}}{3\phi}$, where $\lambda_1(\phi)$ falls from $1/2$ when $\phi = 0$ to $1/3$ when $\phi = 1$,*

(ii) *issue an exclusive license to firm 2 if $\lambda_1(\phi) \leq \lambda_1 < \lambda_1^*$, where λ_1^* is defined in Proposition 1, or if $\lambda_1 \geq \lambda_1^*$ and $\phi < \phi^*$, where $\phi^* \in (0,1)$ is defined by*

$$\phi^* = 1 + \frac{B(\lambda_1, \lambda_2, \lambda_3)}{\lambda_1 \left[(2-\lambda_3)(\lambda_1 - \lambda_2) + \lambda_1(\lambda_2 - \lambda_3)\right]}, \tag{15}$$

with $B(\lambda_1, \lambda_2, \lambda_3)$ being defined in (7); and

(iii) *not issue any licenses if $\lambda_1 \geq \lambda_1^*$ and $\phi > \phi^*$.*

Proof: See the Appendix.

Proposition 4 is illustrated in Figure 3.

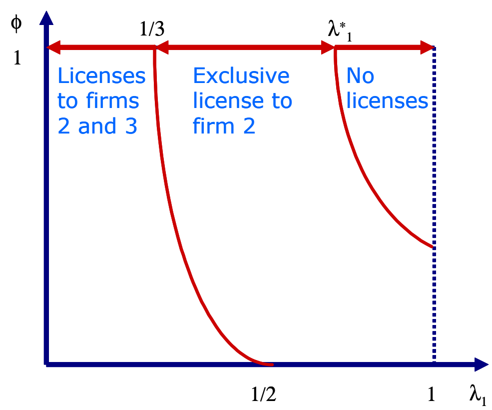

Figure 3: Licensing interim R&D knowledge when firm 1's knowledge is worth more to firms 2 and 3

Noting that Proposition 1 refers to the case where $\phi = 1$ (the upper edge of the square), it follows that a decrease in ϕ, which lowers the probability that firm 1 can successfully develop the new technology on its own, induces firm 1 to issues nonexclusive licenses to both firms 2 and 3 for a broader range of λ_1. Similarly, a decrease in ϕ expands the range of λ_1 values for which firm 1 issues an exclusive license to firm 2 rather than not issue any licenses. When ϕ is sufficiently small, firm 1 never holds on to its technological lead and either issues nonexclusive licenses when λ_1 is relatively small or issues an exclusive license to firm 2 when λ_1 is relatively large.

4.4 Correlation

So far I have assumed that the success probabilities of the three firms are independent of each other and remain so even following licensing agreements. Now, I relax this assumption and assume that once licensing takes place, the success probabilities of the licensor and the licensee(s) become positively correlated.

To capture this correlation in as simple manner as possible, I will assume that if licensing takes place, the success probabilities of firm 1 and its licensee(s) are perfectly correlated with probability ρ, but are completely independent with probability $1-\rho$.[12] With this assumption in place, the expected payoffs of the three firms when firm 1 issues an exclusive license to firm 2 for a license fee T_2 are given by:

$$\pi_1(y,n,\rho) = (1-\rho)\,\lambda_1\,(1-\lambda_1)\,(1-\lambda_3) + T_2, \tag{16}$$

$$\pi_2(y,n,\rho) = (1-\rho)\,\lambda_1\,(1-\lambda_1)\,(1-\lambda_3) - T_2, \tag{17}$$

and

$$\pi_3(y,n,\rho) = \lambda_3\left[\rho\,(1-\lambda_1) + (1-\rho)\,(1-\lambda_1)^2\right]. \tag{18}$$

The expected payoffs when firm 1 licenses its knowledge exclusively to firm 3 are completely analogous. Equations (16)-(18) reflect the fact that firms 1 and 2 can be the sole developers of the new technology only if their success probabilities are independent and only if both their rivals fail. Firm 3 can be the sole developer of the new technology either when the success probability of firms 1 and 2 is perfectly correlated and both fail, or when the success probabilities of firms 1 and 2 are independent and both fail.

[12] For an alternative modelling approach to correlation between the success probabilities of firms that engage in an R&D contest, see for example Dasgupta and Maskin (1987).

When firm 1 issues nonexclusive licenses to both firms 2 and 3, the expected payoffs of the three firms become:

$$\pi_1(y,y,\rho) = (1-\rho)\,\lambda_1(1-\lambda_1)^2 + T_2 + T_3, \tag{19}$$

and

$$\pi_j(y,y,\rho) = (1-\rho)\,\lambda_1(1-\lambda_1)^2 - T_j, \qquad j = 2,3. \tag{20}$$

That is, a firm can be the sole developer of the new technology only if the success probabilities of all three firms are independent and the firm's two rivals fail. When firm 1 does not issue licenses, the expected payoff of each firm i is given by equation (1). Noting that the firms' payoffs decrease with ρ, it is clear that under correlation, firm 1 will issue licenses for a smaller set of parameters than under independence. However, following the same steps as in the proof of Proposition 1, it is easy to verify that the qualitative results of Proposition 1 remain valid so long as the degree of correlation, ρ, is not too large.

Things are different however when ρ is relatively large. In the next proposition, I establish two important differences:

Proposition 5: *In the presence of correlation between the success probabilities of firm* 1 *and its licensees, the following is true:*

(i) *Firm* 1 *will never issue nonexclusive licenses to both firms* 2 *and* 3 *whenever*

$$\rho > \overline{\rho} \equiv \frac{(1-3\lambda_1)\,(\lambda_1-\lambda_2)}{\lambda_1\,(1-3\lambda_1+3\lambda_2)},$$

where $\overline{\rho} \in [0,1]$ *for all* $\lambda_1 < 1/3$.

(ii) *Firm* 1 *will issue an exclusive license to firm* 3 *whenever* $\lambda_1 < 1/3$ *and* $\overline{\rho} < \rho < \widehat{\rho}$, *where*

$$\widehat{\rho} \equiv 1 - \frac{\lambda_1(1-\lambda_2) + \lambda_3(1-2\lambda_1+\lambda_1\lambda_2)}{\lambda_1(1-\lambda_1)(2-2\lambda_2+\lambda_3)},$$

with $\widehat{\rho} \in [0,1]$ *for all* $\lambda_1 < 1/3$.

Proof: See the Appendix.

To interpret Proposition 5, recall from Proposition 1 that under independence ($\rho = 0$), it is optimal for firm 1 to issue nonexclusive licenses to both firms 2 and 3 when $\lambda_1 < 1/3$. Part (i) of Proposition 5 shows however that if ρ is sufficiently large, then such an option is never optimal for firm 1. Part (ii) of the Proposition shows that if $\lambda_1 < 1/3$ and if ρ is not too large, then instead of issuing nonexclusive licenses as in the case of independence, firm 1 will issue an exclusive license to firm 3. Issuing such a license is never optimal under independence.

It should be noted however that for some values of λ_1, λ_2, and λ_3, $\overline{\rho} > \widehat{\rho}$, in which case the set of ρ values for which firm 1 will issue an exclusive license to firm 3 is empty. For example, if $\lambda_2 = 0.07$ and $\lambda_3 = 0$, then $\widehat{\rho} > \overline{\rho}$ only when $\lambda_1 \in (0.07, 0.162) \cup (0.288, 0.33]$; otherwise, if $\lambda_1 \in (0.162, 0.288)$, then $\widehat{\rho} < \overline{\rho}$.

4.5 Bans on exclusive licenses

In this section I consider the consequences of bans on exclusive licensing agreements.[13] At first blush it might be thought that such bans are a good idea since they force firm 1 to license its knowledge to both firms 2 and 3 and thereby not only raise the overall probablity of success, but also raise the likelihood that more than one firm will develop the new technology (in which case there will be competition in the product market instead of monopoly). However, the next proposition shows that such bans may backfire in the sense that if firm 1 cannot issue an exclusive license to firm 2, it may prefer to simply hold on to its technological lead and not issue any licenses.

Proposition 6: *If firm* 1 *is not allowed to issue exclusive licenses then in equilibrium, it will issue nonexclusive licenses to both firms* 2 *and* 3 *if* $\lambda_1 < \lambda_1^{**}$, *where* $1/3 < \lambda_1^{**} < \lambda_1^{*}$, *and will not issue any licenses otherwise.*

[13] In the U.S., exclusive licensing is treated under the "rule of reason," see *Morraine Products v. ICI America Inc.*, 538 F.2d.134 (7th Cir) cert denied, 429 U.S. 941 (1976) (see also Section 3.4 in the 1995 Department of Justice and Federal Trade Commission Antitrust Guidelines for the Licensing of Intellectual Property). There are several important cases in which firms were not allowed to issue exclusive licenses. For example, in two separate consent decrees signed in 1956, AT&T and IBM were required to license their patents on a nonexclusive, world-wide basis to any applicant at a reasonable royalty.

Proof: See the Appendix.

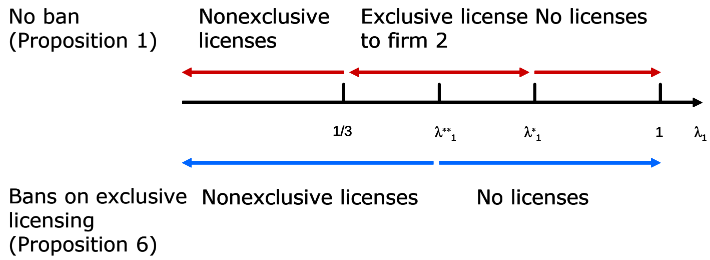

Figure 4: Bans on exclusive licensing of interim R&D knowledge

Figure 4 shows that bans on exclusive licensing have the intended effect only when$1/3 < \lambda_1 < \lambda_1^{**}$: firm 1 then licenses its knowledge to both firms 2 and 3 instead of licensing it exclusively to firm 2. However, when $\lambda_1^{**} < \lambda_1 < \lambda_1^{*}$, bans on exclusive licensing backfire because they induce firm 1 to stop issuing licenses altogether. As a result, there is less dissemination of interim R&D knowledge in this range rather than more.

5 Acquisition of knowledge

In this section I consider the possibility that firm 1 will sell its superior knowledge rather than license it out. The difference between selling and licensing is that when firm 1 sells its knowledge, it exits the R&D contest altogether, whereas under licensing it stays in the contest. For instance, an exclusive sale of knowledge to firm $j = 2, 3$ could correspond to a situation in which firm j acquires firm 1 or acquires the relevant R&D lab or division of firm 1.[14] A nonexclusive sale of knowledge could correspond to the case where firm 1 transfers its knowledge to firms 2 and 3 and commits to exit the R&D contest. In Section 5.1, I study

[14] In the U.S., an outright sale of intellectual property rights by their owner or a license that precludes all other persons, including the licensor, from using the licensed intellectual property "are most appropriately analyzed by applying the principles and standards used to analyze mergers, particularly those in the 1992 Horizontal Merger Guidelines" (see Section 5.7 in the 1995 Department of Justice and Federal Trade Commission Antitrust Guidelines for the Licensing of Intellectual Property).

the pattern of selling agreements that arise in equilibrium. In Section 5.2, I examine firm 1's choice between licensing and selling its knowledge when both options are available.

5.1 Exclusive and nonexclusive sales of knowledge

Assume that after the vector $(\lambda_1, \lambda_2, \lambda_3)$ is realized, firm 1 can make a pair of take-it-or-leave-it offers to firms 2 and 3 in which it offers to sell them its knowledge for fees T_2 and T_3. If both offers are rejected, then the expected payoff of firm 1 is given by equation (1) and the payoffs of firms 2 and 3 are analogous. If only one firm accepts firm 1's offer, then this firm acquires firm 1's knowledge exclusively. If both firms accept, then a tie-breaking rule that will be specified in Lemma 2 below, determines which firm will acquire firm 1's knowledge.

The resulting expected payoffs of the three firms when firm 1's knowledge is acquired exclusively by firm 2 are given by:

$$\pi_1^s(y, n) = T_2, \tag{21}$$

$$\pi_2^s(y, n) = \lambda_1(1 - \lambda_3) - T_2, \tag{22}$$

and

$$\pi_3^s(y, n) = \lambda_3(1 - \lambda_1). \tag{23}$$

The expected payoffs when firm 1 sells its knowledge exclusively to firm 3 are analogous. If firm 1 sells its knowledge to both firms 2 and 3, then the expected payoffs are:

$$\pi_1^s(y, y) = T_2 + T_3, \tag{24}$$

and

$$\pi_j^s(y, y) = \lambda_1(1 - \lambda_1) - T_j, \qquad j = 2, 3. \tag{25}$$

The following lemma is the analog of Lemma 1 for the case of sales of knowledge:

Lemma 2: *Suppose that firm 1 wishes to sell its knowledge exclusively to firm $j = 2, 3$. Then, the optimal scheme from its perspective is to make each take-it-or-leave-it offers with*

$$T_j^s = \lambda_1(1 - \lambda_k) - \lambda_j(1 - \lambda_1), \qquad k \neq j,$$

and

$$T_k^s = 0,$$

and set a tie-breaking rule that specifies that firm 1's knowledge will be sold exclusively to firm j if both firms accept their respective offers. If firm 1 wishes to sell its knowledge to both firms 2 and 3, then the optimal scheme from its perspective is to set

$$\widehat{T}_j^s = (\lambda_1 - \lambda_j)(1 - \lambda_1), \qquad j = 2, 3,$$

and set a tie-breaking rule that specifies that firm 1's knowledge will be sold to both firms if both accept their respective offers.

The proof is completely analogous to the proof of Lemma 1 and hence is omitted. Note that the licensing fees under selling are $1/(1-\lambda_1)$ times the corresponding fees under licensing. This reflects the fact that when firm 1 sells it knowledge it exits the contest and hence does not pose a competitive threat to its licensee(s).

The next result characterizes firm 1's decision when it can only sell its knowledge to rival but not license it.

Proposition 7: *In equilibrium, firm 1 will*

(i) *sell its knowledge to both firms 2 and 3 if* $\lambda_1 < 1/2$ and $(\lambda_1 - \lambda_2 - \lambda_3)(1 - 2\lambda_1) > \lambda_1\lambda_2\lambda_3$;

(ii) *not sell its knowledge if* $\lambda_1 < 1/2$ and $(\lambda_1 - \lambda_2 - \lambda_3)(1 - 2\lambda_1) < \lambda_1\lambda_2\lambda_3$ or if $1/2 \leq \lambda_1 < 1/(2 - \lambda_3)$, *where* $1/(2 - \lambda_3) < \lambda_1^*$;

(iii) *sell its knowledge exclusively to firm 2 if* $\lambda_1 > 1/(2 - \lambda_3)$.

Proof: If firm 1 sells its knowledge exclusively to firm 2 at T_2^s, then its expected payoff is

$$\pi_1^{s*}(y, n) = \lambda_1(1 - \lambda_3) - \lambda_2(1 - \lambda_1). \tag{26}$$

If it sells its knowledge exclusively to firm 3 at T_3^s, then its expected payoff is

$$\pi_1^{s*}(n, y) = \lambda_1(1 - \lambda_2) - \lambda_2(1 - \lambda_1). \tag{27}$$

If firm 1 sells its knowledge to both firms 2 and 3 for $\widehat{T}_2^s$ and $\widehat{T}_3^s$, then its expected payoff is

$$\pi_1^{s*}(y, y) = (1 - \lambda_1)(2\lambda_1 - \lambda_2 - \lambda_3). \tag{28}$$

And, if firm 1 holds on to its knowledge, then its expected payoff is given by equation (1).

Comparing equations (26)-(28) reveals that since $\lambda_1 > \lambda_2 \geq \lambda_3$, then $\pi_1^{s*}(y,y) > \max\{\pi_1^{s*}(y,n), \pi_1^{s*}(n,y)\}$ for all $\lambda_1 < 1/2$, and $\pi_1^{s*}(y,n) > \max\{\pi_1^{s*}(y,y), \pi_1^{s*}(n,y)\}$ for all $\lambda_1 > 1/2$. That is, if firm 1 wishes to sell its knowledge, then it will sell it either to both firms if $\lambda_1 < 1/2$, or exclusively to firm 2 if $\lambda_1 > 1/2$.

To examine whether firm 1 will sell its knowledge at all, suppose first that $\lambda_1 \leq 1/2$. Then, firm 1 needs to decide between selling to both firms 2 or 3 or not selling it all. Using equations (28) and (1) yields,

$$\begin{aligned} \pi_1^{s*}(y,y) - \pi_1(n,n) &= (1-\lambda_1)(2\lambda_1 - \lambda_2 - \lambda_3) - \lambda_1(1-\lambda_2)(1-\lambda_3) \\ &= (\lambda_1 - \lambda_2 - \lambda_3)(1-2\lambda_1) - \lambda_1\lambda_2\lambda_3. \end{aligned}$$

Hence, the expression in the proposition.

Next, suppose that $\lambda_1 > 1/2$, so that if firm 1 sells its knowledge at all, it will sell it exclusively to firms 2. Using equations (26) and (1), yields

$$\pi_1^{s*}(y,n) - \pi_1(n,n) = \lambda_2(2-\lambda_3)\left(\lambda_1 - \frac{1}{2-\lambda_3}\right).$$

Hence, firm 1 will sell its knowledge exclusively to firm 2 if $\lambda_1 > 1/(2-\lambda_3)$, and will not sell it at all if $1/2 \leq \lambda_1 < 1/(2-\lambda_3)$, where by Proposition 1, $1/(2-\lambda_3) < \lambda_1^*$. ■

Proposition 7 is illustrated in Figure 5.

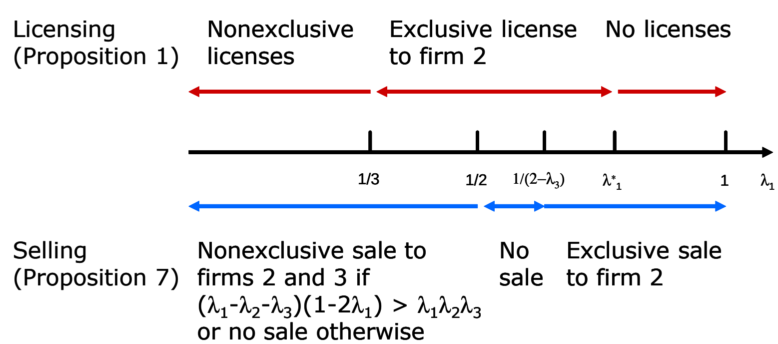

Figure 5: Exclusive and nonexclusive sale of interim R&D knowledge

When λ_1 is sufficiently large, i.e., above $1/(2-\lambda_3)$, firm 1 prefers to sell its knowledge exclusively to firm 2. On the other hand, when λ_1 is intermediate, i.e., above $1/2$ and below

$1/(2-\lambda_3)$, firm 1 prefers to hold on to its technological lead. Note that the higher λ_3, the larger λ_1 has to be to ensure that selling to firm 2 is optimal. Intuitively, both T_2^s and T_3^s decreases with λ_3, since the more likely firm 3 is to develop the new technology on its own, the less keen firm 2 is on acquiring firm 1's knowledge (there is a high probability that it will not be the sole developer of the new technology), and the less valuable firm 1's knowledge is to firm 3. This renders a sale of knowledge less attractive to firm 1.

As λ_1 drops below 1/2, firm 1 may wish to sell its knowledge to both firms 2 and 3 instead of holding on to its technological lead, provided that $(\lambda_1 - \lambda_2 - \lambda_3)(1 - 2\lambda_1) > \lambda_1\lambda_2\lambda_3$. Notice that this condition surely fails when $\lambda_1 = 1/2$ or when $\lambda_1 \leq \lambda_2 + \lambda_3$. By continuity, firm 1 would not wish to sell its knowledge unless λ_1 is sufficiently below 1/2 and sufficiently above $\lambda_2 + \lambda_3$. On the other hand, the condition surely holds when $\lambda_3 = 0$ (firm 3 is far behind firm 1), and by continuity, when λ_3 is close to 0.

5.2 Sell or license?

The next step is to examine whether firm 1 would wish to license its knowledge or sell it if it can choose between the two alternatives.

Proposition 8: *Suppose that firm 1 can either license its knowledge, sell its knowledge, or hold on to its technological lead. Then, firm* 1 *will*

(i) *license its knowledge to both firms* 2 *and* 3 *if* $\lambda_1 < 1/3$,

(ii) *license its knowledge exclusively to firm* 2 *if* $1/3 \leq \lambda_1 < \lambda_1^*$, *and*

(iii) *sell its knowledge exclusively to firm* 2 *if* $\lambda_1 \geq \lambda_1^*$.

Proof: See the Appendix.

Proposition 8 is illustrated in Figure 6. It shows that whenever firm 1 can choose between licensing and selling, it will never hold on to its technological lead and will either license or sell its interim R&D knowledge. Selling is optimal when λ_1 is large (firm 1 is highly likely to develop the new technology) because firm 1 exits the contest after selling its knowledge, so the acquirer enjoys a high probability of being the sole developer of the new technology. Licensing is not attractive in this case because it raises the likelihood that more than one firm will succeed and competition in the product market will drive profits to 0. When λ_1 is small, firm 1 prefers to license its interim knowledge rather than sell it because under licensing, firm 1 stays in the contest so the overall probability that at least one firm will develop the new technology is higher than under selling.

Figure 6: Selling or licensing?

6 Non-Blackwell ordered knowledge

So far I have assumed that the knowledge of the three firms can be Blackwell ordered: firm 3's knowledge is a subset of firm 2's knowledge, which is in turn a subset of firm 1's knowledge. In this section I relax this assumption and assume instead that while the success probabilities are still such that $\lambda_1 > \lambda_2 \geq \lambda_3$, these probabilities correspond to three different approaches to R&D. Hence, when firm j licenses in firm i's knowledge, it has access to two different approaches to R&D: its own original approach, and firm i's approach. Consequently, the success probability of firm j becomes $\widetilde{\lambda}_{ji} = 1 - (1 - \lambda_i)(1 - \lambda_j)$: firm j succeeds unless both its own approach and firm i's approach fail.[15] This situation differs from the one considered earlier in two ways. First, the knowledge of every firm is now useful to the other two firms. Second, firm 1's knowledge is now more useful to firms 2 and 3 because if firm $j = 2, 3$ licenses in firm 1's knowledge, then its success probability increases by $\widetilde{\lambda}_{j1} - \lambda_j = \lambda_1 - \lambda_1\lambda_j$,

[15] I will retain however the assumption that the success probabilities of the three firms are uncorrelated even if they engage in licensing.

whereas earlier it has increased by merely $\lambda_1 - \lambda_j$. As before, the expected payoff of each firm i absent licensing is given by equation (1).

6.1 Unilateral licensing agreements

I begin the analysis by considering the case where only firm i can issue licenses. This case is a natural starting point because it provides a straightforward extension of the situation considered in Proposition 1. The only difference is that now, the licensor does not have to be firm 1 since the knowledge of every firm is useful for the other two firms.

Proposition 9: *Suppose that only firm i can license out its interim R&D knowledge. Then firm i will issue nonexclusive licenses to both rivals if $\lambda_i < \widetilde{\lambda}_i^*$, and will not issue any licenses otherwise; $\widetilde{\lambda}_i^*$ is defined implicitly by the equation*

$$\frac{2-\lambda_j-\lambda_k}{(1-\lambda_j)(1-\lambda_k)} = \frac{\lambda_i(2-\lambda_i)}{1-\lambda_i},$$

and is increasing with λ_j and λ_k, and $\widetilde{\lambda}_i^* \geq 2-\sqrt{2}$.

Proof: First, note that firm i's expected payoff when it issues an exclusive license to firm j while "threatening" to transfer its entire knowledge to firm $k \neq i, j$ if its offer is rejected, is given by

$$\begin{aligned}
\widetilde{\pi}_{ij} &= \lambda_i\left(1-\widetilde{\lambda}_{ji}\right)(1-\lambda_k) + \left[\widetilde{\lambda}_{ji}(1-\lambda_i)(1-\lambda_k) - \lambda_j(1-\lambda_i)(1-\widetilde{\lambda}_{ki})\right] \\
&= \lambda_i(1-\lambda_i)(2-\lambda_j)(1-\lambda_k),
\end{aligned}$$

where $\lambda_i\left(1-\widetilde{\lambda}_{ji}\right)(1-\lambda_k)$ is the probability that firm i will be the sole developer of the new technology under an exclusive license to firm j, and the square bracketed term is the difference between the probability that firm j will be the sole developer of the new technology when it gets an exclusive license from firm i and when firm $k \neq j$ gets such an exclusive license. On the other hand, if firm i issues nonexclusive licenses to both firms j and k, then its expected payoff is

$$\begin{aligned}
\widetilde{\pi}_i(y,y) &= \lambda_i\left(1-\widetilde{\lambda}_{ji}\right)\left(1-\widetilde{\lambda}_{ki}\right) + \left[\widetilde{\lambda}_{ji}(1-\lambda_i)(1-\lambda_k) - \lambda_j(1-\lambda_i)(1-\widetilde{\lambda}_{ki})\right] \\
&\quad + \left[\widetilde{\lambda}_{ki}(1-\lambda_i)(1-\lambda_j) - \lambda_k(1-\lambda_i)(1-\widetilde{\lambda}_{ji})\right] \\
&= \lambda_i(1-\lambda_i)\left[(1-\lambda_i)(1-\lambda_j)(1-\lambda_k) + (2-\lambda_j-\lambda_k)\right].
\end{aligned}$$

Now, notice that

$$\widetilde{\pi}_i(y,y) - \widetilde{\pi}_{ij} = \lambda_i \left(1-\lambda_i\right)\left(1-\lambda_j\right)(1-\lambda_i+\lambda_i\lambda_k) > 0.$$

Hence, nonexclusive licenses to both rivals dominate exclusive licenses to just one rival. Moreover,

$$\widetilde{\pi}_i(y,y) - \pi_i(n,n) = \lambda_i \left(1-\lambda_i\right)\left(1-\lambda_j\right)\left(1-\lambda_k\right)\left[\frac{2-\lambda_j-\lambda_k}{\left(1-\lambda_j\right)\left(1-\lambda_k\right)} - \frac{\lambda_i\left(2-\lambda_i\right)}{1-\lambda_i}\right].$$

Noting that $\frac{2-\lambda_j-\lambda_k}{(1-\lambda_j)(1-\lambda_k)}$ is positive and independent of λ_i, while $\frac{\lambda_i(2-\lambda_i)}{1-\lambda_i}$ increases monotonically with λ_i from 0 when $\lambda_i = 0$ to infinity when $\lambda_i = 1$, it follows that there exists a unique value of λ_i, denoted $\widetilde{\lambda}_i^*$, such that $\widetilde{\pi}_i(y,y) > \pi_i(n,n)$ for $\lambda_i < \widetilde{\lambda}_i^*$ and $\widetilde{\pi}_i(y,y) < \pi_i(n,n)$ for $\lambda_i > \widetilde{\lambda}_i^*$, where $\widetilde{\lambda}_i^*$ is the value of λ_i at which the bracketed term vanishes. Finally, $\frac{2-\lambda_j-\lambda_k}{(1-\lambda_j)(1-\lambda_k)}$ attains its lowest value when $\lambda_j = \lambda_k = 0$; in that case, $\widetilde{\lambda}_i^* = 2-\sqrt{2}$. For all $\lambda_j > 0$ and $\lambda_k > 0$, $\frac{2-\lambda_j-\lambda_k}{(1-\lambda_j)(1-\lambda_k)}$ is higher and hence $\widetilde{\lambda}_i^*$ is higher. ■

Proposition 9 indicates that firm i will never issue an exclusive license when the interim knowledge of the three firms is non-Blackwell ordered. Instead, it will either issue licenses to both rivals if λ_i is relatively small, or will not issue any licenses. This situation is very different than the one considered in Section 3 where it was optimal for firm 1 to issue an exclusive license to firm 2 when λ_1 was intermediate. The situation in the two cases is qualitatively similar however when λ_1 is either small (in both cases firm 1 issues nonexclusive licenses to firms 2 and 3) or large (in both cases firm 1 does not issue any licenses).

Unfortunately, there is no obvious way to determine which unilateral licensing agreements will emerge if the three firms can freely bargain with each other. However, to the extent that these agreements will be efficient (i.e., generate the highest joint expected profit), it is interesting to examine which nonexclusive licensing arrangements maximize the joint expected payoff of the three firms.

Proposition 10: *Suppose that only firm i can license out its interim R&D knowledge, and let $\delta_j \equiv 1-\lambda_j$ denote the probability that firm $j = 1,2,3$ fails (note that $\delta_1 < \delta_2 \leq \delta_3$). Then the joint expected payoff of the three firms is maximized when the licensor is*

(i) *firm 1 if $\delta_1 + \delta_2 > H$,*

(ii) *firm* 2 *if* $\delta_1 + \delta_2 < H < \delta_2 + \delta_3$, *and*

(iii) *firm* 3 *if* $\delta_2 + \delta_3 < H$,

where $H \equiv \frac{1}{3}\left(1 + \frac{\delta_1\delta_2 + \delta_1\delta_3 + \delta_2\delta_3}{\delta_1\delta_2\delta_3}\right)$.

Proof: See the Appendix.

Proposition 10 implies that in general, there is no reason to expect that in equilibrium, firm 1 will be the licensor. Whenever the sum of the success probabilities of firms 1 and 2 is relatively large (i.e., the sum of their probabilities of failure, $\delta_1 + \delta_2$, is sufficiently small), then it is efficient for the three firms to let firms 2 or 3 issue nonexclusive licenses.

6.2 Cross-licensing agreements

When interim R&D knowledge is non-Blackwell ordered, the knowledge of each firm is useful to each of its two rivals. Hence, the three firms may wish to engage in cross licensing agreements. For instance, the three firms may engage in a three-way cross-licensing agreement whereby they all share each other's knowledge. Alternatively, firms i and j may engage in a bilateral cross-licensing agreement, with firm k either engaging in a unilateral licensing agreement with firm i, or with firm j, or with both, or not engaging in any licensing agreement. Moreover, firm k can either be the licensor or the licensee in such unilateral licensing agreements. Given the large number of possibilities, it is obvious that a full-blown analysis of cross-licensing agreements would require a separate paper. In what follows, I will simply show that the joint expected payoff of the three firms can be higher with cross-licensing agreements than with unilateral licensing agreements.

To this end, consider first a three-way cross-licensing agreement, in which all three firms share each other's interim R&D knowledge. Recalling from Proposition 10 that δ_i is the probability that firm i fails, the success probability of each firm under a three-way cross-licensing agreement is $1 - \delta_1\delta_2\delta_3$. That is, each firm succeeds unless the R&D approaches of all three firms fail. Hence, the joint expected payoff of the three firms becomes

$$V_{123} = 3\left(1 - \delta_1\delta_2\delta_3\right)\left(\delta_1\delta_2\delta_3\right)^2,$$

where $1-\delta_1\delta_2\delta_3$ is the probability that one of the three firms succeeds and $(\delta_1\delta_2\delta_3)^2$ is the probability that both of its rivals fail.

Now, suppose that $\delta_1+\delta_2>H$. By Proposition 10, the most profitable unilateral agreement in this case is the one in which firm 1 licenses out its interim R&D knowledge to firms 2 and 3. To show that a three-way cross-licensing agreement can be even more profitable, note that

$$\begin{aligned} V_{123}-\widetilde{\Pi}_1(y,y) &= 3(1-\delta_1\delta_2\delta_3)(\delta_1\delta_2\delta_3)^2-\delta_1^2[\delta_2+\delta_3+\delta_2\delta_3(1-3\delta_1)] \\ &= 3\delta_1^2\delta_2\delta_3\left(1-\delta_2^2\delta_3^2\right)[\delta_1-L(\delta_2,\delta_3)], \end{aligned}$$

where $L(\delta_2,\delta_3)\equiv\frac{1+\frac{\delta_2+\delta_3}{\delta_2\delta_3}-3\delta_2\delta_3}{3\left(1-\delta_2^2\delta_3^2\right)}$. This expression is positive if and only if $\delta_1>L(\delta_2,\delta_3)$. Since $\delta_2>\delta_1$, there exist values of δ_1 for which $\delta_1>L(\delta_2,\delta_3)$ only if $\delta_2>L(\delta_2,\delta_3)$. To illustrate, suppose that $\delta_2=\delta_3$. Then $\delta_2>L(\delta_2,\delta_2)$ for all $\delta_2>0.84$. Hence, for all $\delta_2>0.84$, one can find values of δ_1 such that $V_{123}>\widetilde{\Pi}_1(y,y)$. Otherwise, there do not exist values of δ_1 such that $\delta_1>L(\delta_2,\delta_3)$, so $V_{123}<\widetilde{\Pi}_1(y,y)$.

Now, let me show that bilateral cross-licensing agreements could also yield a higher joint expected payoff for the three firms than unilateral nonexclusive licenses. To this end, note that if firms i and j reach a bilateral cross-licensing agreement, then the success probability of each of them becomes $1-\delta_i\delta_j$, while the success probability of firm $k\neq i,j$ remains $\lambda_k\equiv 1-\delta_k$. Hence, the aggregate expected payoff of the three firms is

$$V_{ij}=2(1-\delta_i\delta_j)\delta_i\delta_j\delta_k+(1-\delta_k)(\delta_i\delta_j)^2,$$

where $2(1-\delta_i\delta_j)\delta_i\delta_j\delta_k$ is the probability that either firm i or firm j succeeds while the other two firms fail, and $(1-\delta_k)(\delta_i\delta_j)^2$ is the probability that firm k succeeds while firms i and j fail.

Assuming one again that $\delta_1+\delta_2>H$, the highest joint expected payoff of the three firms under unilateral licensing is attained when firm 1 issues nonexclusive licenses to firms 2 and 3. Now, let me compare $\widetilde{\Pi}_1(y,y)$ with the joint expected payoff when firms 1 and 2 reach a bilateral cross-licensing agreement:

$$\begin{aligned} V_{12}-\widetilde{\Pi}_1(y,y) &= 2(1-\delta_1\delta_2)\delta_1\delta_2\delta_3+(1-\delta_3)(\delta_1\delta_2)^2-\delta_1^2[\delta_2+\delta_3+\delta_2\delta_3(1-3\delta_1)] \\ &= \delta_1\left[2\delta_2\delta_3-\delta_1\left(\delta_2+\delta_3+\delta_2\delta_3(1-3\delta_1)-\delta_2^2(1-3\delta_3)\right)\right]. \end{aligned}$$

To show that this expression could be either positive or negative, let $\delta_2 = \delta_3 = \delta$. Then

$$V_{12} - \widetilde{\Pi}_1 (y, y) = 3\delta_1\delta (\delta - \delta_1) \left(\frac{2}{3} - \delta\delta_1 \right).$$

Since $\delta_1 < \delta$, it follows that $V_{12} > \widetilde{\Pi}_1 (y, y)$ if and only if $\delta\delta_1 < \frac{2}{3}$. For example if $\delta_2 = \delta_3 = 0.9$, then $V_{12} > \widetilde{\Pi}_1 (y, y)$ provided that $\delta_1 < 0.741$.

7 Conclusion

In this paper I have examined the incentives of firms to engage in licensing of precommercial, interim R&D knowledge. This knowledge boosts the success probability of the licensees but does not guarantee it. I have shown that in a broad range of cases, the leading firm in the R&D contest will prefer to license its superior knowledge to one of the lagging rivals or to both rather than hold on to its technological lead. Such licensing agreements have two main advantages from the leading firm's point of view: First, they have the potential to create value by increasing the chance that the licensee(s) will develop the new technology when the leading firm fails. The leading firm in turn can capture this value through the license fee(s) that it charges. Value creation is not guaranteed however since the licensing agreements also raise the probability that both the licensor and the licensee(s) will develop the new technology and will end up competing in the product market. Second, licensing agreement(s) allow the leading firm to extract surplus from the lagging firms as each licensee(s) pay(s) not only for access to the leading firm's superior knowledge, but also in order to ensure that the remaining firm will not obtain exclusive access to this knowledge.

There clearly remain a number of interesting extensions that must be addressed before we have a good understanding of the incentives to engage in licensing of interim R&D knowledge and their implication. I will now mention just a few of these extensions. First, I have treated the success probabilities of the three firms as exogenous parameters. A natural extension then would be to add an initial stage to the model at which the three firms choose how much to invest in R&D; these investments in turn determine the vector $(\lambda_1, \lambda_2, \lambda_3)$. Moreover, one can also add a second investment stage which takes place after the licensing agreements are reached. For example, one can assume that the overall success probability of firm i is given by $p(\lambda_i, \tau_i)$, where τ_i is firm i's second stage investment, and $p(\cdot,\cdot)$ increases in both arguments. In such a model, licensing will have an added advantage of allowing the licensee(s) to obtain the leading firm's knowledge without having to costly develop it. Moreover, such a model will also make it possible to explore in more detail the competitive effects of bans on exclusive licensing since these bans will not only affect the licensing of interim R&D knowledge but will also affect investments in R&D.

Second, throughout the paper I have assumed that the vector of success probabilities, $(\lambda_1, \lambda_2, \lambda_3)$, is common knowledge. While this assumption is a natural starting point and establishes an important benchmark, it would be interesting in future research to relax it and examine the case where λ_i is private information for firm i. This extension is obviously much harder than the first extension because it involves multilateral bargaining under asymmetric information. As mentioned in the Introduction, two papers that make a progress in this direction are d'Aspremont, Bhattacharya, and Gerard-Varet (2000) and Bhattacharya and Guriev (2006). These papers however consider somewhat simpler situations than the one considered here because there are only two firms in the first paper and because the licensor in the second paper is an outside research lab that cannot develop the final product.

Finally, in Section 6 of the paper I have only briefly considered licensing of non-Blackwell ordered interim R&D knowledge. In future research it would be useful to study a full-blown model of multilateral bargaining among three or more firms over licensing of such knowledge and examine the conditions under which firms reach unilateral licensing agreements, cross-licensing agreements, or a mixture of both.

8 Appendix

Following are the proofs of Propositions 2, 4-6, 8, and 10.

Proof of Proposition 2: Differentiating $\pi_1(\Delta_2, \Delta_3)$ with respect to Δ_j, $j = 2, 3$, yields

$$\begin{aligned} \frac{\partial \pi_1(\Delta_2, \Delta_3)}{\partial \Delta_j} &= (1-3\lambda_1)(1-\lambda_k-\Delta_k) + (\lambda_1-\lambda_k-\Delta_k) \\ &= (1-2\lambda_1)(1-\lambda_k-\Delta_k) - (1-\lambda_1)(\lambda_k+\Delta_k), \end{aligned} \tag{29}$$

where $k \neq j$. From the first line of (29) it is clear that $\frac{\partial \pi_1(\Delta_2,\Delta_3)}{\partial \Delta_j} > 0$, $j = 2, 3$ when $\lambda_1 \leq 1/3$, whereas from the second line it is clear that $\frac{\partial \pi_1(\Delta_2,\Delta_3)}{\partial \Delta_j} < 0$, $j = 2, 3$, when $1/2 \le \lambda_1 \le 1$. Hence, firm 1 will license its entire knowledge to firms 2 and 3 if $\lambda_1 \le 1/3$, but will prefer to transfer them as little knowledge as possible if $\lambda_1 \ge 1/2$. Assuming that it is possible to sign licensing agreements in which virtually no knowledge is transferred, and recalling that $\pi_1(0,0) > \pi_1(n,n)$, it follows that whenever $\lambda_1 \ge 1/2$, firm 1 will issue nonexclusive licenses to firms 2 and 3 and will transfer them virtually no knowledge.

The remaining question is what happens when $1/3 < \lambda_1 < 1/2$. To address this question, suppose that firm 1 licenses its entire knowledge to firm k. Then, $\frac{\partial \pi_1(\Delta_2,\Delta_3)}{\partial \Delta_j} = (1 - 3\lambda_1)(1 - \lambda_1) < 0$, where the inequality follows since $\lambda_1 > 1/3$. Hence, firm 1 would like to set $\Delta_j = 0$. Consequently, firm 1 will never license its entire knowledge to both firms 2 and 3. Rather, it will either license its entire knowledge exclusively to firm 2 or to firm 3, or issue nonexclusive licenses to both firms and transfers them virtually no knowledge. However, Proposition 1 shows that whenever $\lambda_1 > 1/3$, an exclusive license to firm 2 dominates an exclusive license to firm 3. Hence, if firm 1 issues an exclusive license, it will issue it to firm 2. This implies in turn that in equilibrium, it must be the case that $\Delta_3 = 0$. Substituting $\Delta_3 = 0$ in (29) reveals that

$$\begin{aligned}\frac{\partial \pi_1(\Delta_2,0)}{\partial \Delta_2} &= 1 - 2\lambda_3 - \lambda_1(2 - 3\lambda_3) \\ &= (2 - 3\lambda_3)\left[\frac{1 - 2\lambda_3}{2 - 3\lambda_3} - \lambda_1\right].\end{aligned}$$

Therefore, firm 1 will transfer its entire knowledge exclusively to firm 2 if $\lambda_1 < \frac{1-2\lambda_3}{2-3\lambda_3}$ and will issue nonexclusive licenses to both firms if $\lambda_1 \ge \frac{1-2\lambda_3}{2-3\lambda_3}$, where $\frac{1-2\lambda_3}{2-3\lambda_3}$ decreases from 1/2 when $\lambda_3 = 0$ to 0 when $\lambda_3 = 1/2$ (recall that $\lambda_3 < \lambda_1 < 1/2$). ■

Proof of Proposition 4: Given that firm 1's probability to develop the new technology is $\phi\lambda_1$, equations (8)-(10) and (1) become

$$\pi_1^*(y,n,\phi) = \phi\lambda_1(1-\lambda_1)(1-\lambda_3) + \left[\lambda_1(1-\phi\lambda_1)(1-\lambda_3) - \lambda_2(1-\phi\lambda_1)(1-\lambda_1)\right], \quad (30)$$

$$\pi_1^*(n,y,\phi) = \phi\lambda_1(1-\lambda_2)(1-\lambda_1) + \left[\lambda_1(1-\phi\lambda_1)(1-\lambda_2) - \lambda_3(1-\phi\lambda_1)(1-\lambda_1)\right], \quad (31)$$

$$\begin{aligned}\pi_1^*(y,y,\phi) &= \phi\lambda_1(1-\lambda_1)^2 + \left[\lambda_1(1-\phi\lambda_1)(1-\lambda_1) - \lambda_2(1-\phi\lambda_1)(1-\lambda_1)\right] \quad (32)\\ &\quad + \left[\lambda_1(1-\phi\lambda_1)(1-\lambda_1) - \lambda_3(1-\phi\lambda_1)(1-\lambda_1)\right],\end{aligned}$$

and

$$\pi_1(n,n,\phi) = \phi\lambda_1(1-\lambda_2)(1-\lambda_3). \tag{33}$$

Comparing equations (30)-(32) reveals that since $\lambda_1 > \lambda_2 \geq \lambda_3$, then $\pi_1^*(y,y) > \max\{\pi_1^*(y,n), \pi_1^*(n,y)\}$ for all $\lambda_1 < \lambda_1(\phi) \equiv \frac{1+\phi-\sqrt{1-\phi+\phi^2}}{3\phi}$, and $\pi_1^*(y,n,\phi) > \max\{\pi_1^*(y,y,\phi), \pi_1^*(n,y,\phi)\}$ for all $\lambda_1(\phi) < \lambda_1 < 1$, where $\lambda_1(\phi)$ falls from 1/2 when $\phi \to 0$ to 1/3 when $\phi \to 1$. Hence, if firm 1 issues licenses at all, it will issue nonexclusive licenses to both firms 2 and 3 if $\lambda_1 < \lambda_1(\phi)$ and will issue an exclusive license to firm 2 if $\lambda_1(\phi) < \lambda_1 < 1$.

Now suppose that $\lambda_1 < \lambda_1(\phi)$ and let $H(\phi) \equiv \pi_1^*(y,y,\phi) - \pi_1(n,n,\phi)$. Using equations (32) and (33),

$$\begin{aligned} H(\phi) \equiv\ & (1-\lambda_1)(2\lambda_1 - \lambda_2 - \lambda_3) \\ & +\phi\lambda_1\left[(1-\lambda_1)(1-3\lambda_1+\lambda_2+\lambda_3) - (1-\lambda_2)(1-\lambda_3)\right]. \end{aligned}$$

Clearly, firm 1 will issue nonexclusive licenses to both firms 2 and 3 rather than not issue any licenses provided that $H(\phi) > 0$. Since $(1-\lambda_1) < (1-\lambda_2)$ and $(1-3\lambda_1+\lambda_2+\lambda_3) < (1-\lambda_3)$, it follows that $H'(\phi) < 0$. Moreover, evaluated at $\phi = 1$,

$$H(1) = (1-\lambda_1)^2(3\lambda_1 - \lambda_2 - \lambda_3) - \lambda_1(1-\lambda_2)(1-\lambda_3).$$

Notice that evaluated at $\phi = 1$, $\lambda_1(\phi)$ which is the upper bound on λ_1, is equal to 1/3. It is easy to verify that $H(1)$ is an inverse U-shaped function of λ_1 for all $\lambda_1 \leq 1/3$. Hence, $H(1)$ attains its lowest value either when $\lambda_1 = 0$ or when $\lambda_1 = 1/3$. But, when $\lambda_1 \to 0$, then $H(1) \to 0$ since $\lambda_1 > \lambda_2 \geq \lambda_3$, and when $\lambda_1 = 1/3$, then $H(1) = (1-\lambda_2-\lambda_3-3\lambda_2\lambda_3)/9 > 0$, where the inequality follows because $1/3 = \lambda_1 > \lambda_2 \geq \lambda_3$. Hence, $H(\phi) > 0$ for all $\phi \in [0,1]$, implying that whenever $\lambda_1 < \lambda_1(\phi)$, firm 1 is better off issuing nonexclusive licenses to firms 2 and 3 than not issuing any licenses.

Next, suppose that $\lambda_1 \geq \lambda_1(\phi)$. Then, if firm 1 issues licenses at all, it issues an exclusive license to firm 2. To determine if issuing an exclusive license to firm 2 dominates issuing no licenses at all, let $M(\phi) \equiv \pi_1^*(y,n,\phi) - \pi_1(n,n,\phi)$. Using equations (30) and (33),

$$M(\phi) \equiv B(\lambda_1,\lambda_2,\lambda_3) + (1-\phi)\lambda_1\left[(2-\lambda_3)(\lambda_1-\lambda_2) + \lambda_1(\lambda_2-\lambda_3)\right]. \tag{34}$$

Noting that the square brackets term in $M(\phi)$ is strictly positive, it follows that $M'(\phi) < 0$. Moreover, note that $M(0) = (\lambda_1-\lambda_2) + \lambda_1(\lambda_2-\lambda_3) > 0$ and $M(1) = B(\lambda_1,\lambda_2,\lambda_3)$. Since

Proposition 1 implies that $B(\lambda_1, \lambda_2, \lambda_3) > 0$ for all $\lambda_1 < \lambda_1^*$, it follows that whenever $\lambda_1 < \lambda_1^*$, then $M(\phi) > 0$ for all $\phi \in [0, 1]$. Consequently, whenever $\lambda_1(\phi) \leq \lambda_1 < \lambda_1^*$ (this interval exists since $\lambda_1(\phi) \leq 1/2$ and since Proposition 1 implies that $\lambda_1^* > 1/2$), it is optimal for firm 1 to issue an exclusive license to firm 2, irrespective of the value of ϕ.

On the other hand, when $\lambda_1 \geq \lambda_1^*$, Proposition 1 implies that $B(\lambda_1, \lambda_2, \lambda_3) < 0$. Hence, for each $\lambda_1 \geq \lambda_1^*$, there exists a unique value of $\phi \in (0, 1)$, denoted ϕ^*, such that $M(\phi) > (<) 0$ for all $\phi < (>) \phi^*$. The value of ϕ^* reported in (15) is given by the solution to $M(\phi) = 0$. Consequently, whenever $\lambda_1 \geq \lambda_1^*$, it is optimal for firm 1 to issue an exclusive license to firm 2 if $\phi < \phi^*$ and issue no licenses at all if $\phi > \phi^*$. ■

Proof of Proposition 5: First, note that at the optimum, the license fees under exclusive licenses, T_2^* and T_3^*, are given by the solutions to $\pi_2(y, n, \rho) = \pi_2(n, y, \rho)$ and $\pi_3(n, y, \rho) = \pi_3(y, n, \rho)$, while the license fees under nonexclusive licenses, $\widehat{T}_2^*$ and $\widehat{T}_3^*$, are given by the solutions to $\pi_2(y, y, \rho) = \pi_2(n, y, \rho)$ and $\pi_3(y, y, \rho) = \pi_3(y, n, \rho)$. That is, the license fees are set such that each licensee receives the same payoff as in the case where firm 1 issues an exclusive license to the rival firm. Given T_2^*, T_3^*, $\widehat{T}_2^*$, and $\widehat{T}_3^*$, the expected payoff of firm 1 when it issues an exclusive license to firm 2 is given by:

$$\pi_1^*(y, n, \rho) = \pi_1^*(y, n) - \rho\lambda_1 (1 - \lambda_1) (2 + \lambda_2 - 2\lambda_3), \tag{35}$$

its expected payoff when it issues an exclusive license to firm 3 is given by

$$\pi_1^*(n, y, \rho) = \pi_1^*(n, y) - \rho\lambda_1 (1 - \lambda_1) (2 + \lambda_3 - 2\lambda_2), \tag{36}$$

and its expected payoff when it issues nonexclusive licenses to firms 2 and 3 is given by

$$\pi_1^*(y, y, \rho) = \pi_1^*(y, y) - \rho\lambda_1 (1 - \lambda_1) (3 + \lambda_2 + \lambda_3 - 3\lambda_1), \tag{37}$$

where $\pi_1^*(y, n)$, $\pi_1^*(n, y)$, and $\pi_1^*(y, y)$ are given by (8), (9, and (10). When firm 1 does not issue any licenses, its expected payoff is given by equation (1).

(i) To prove that firm 1 will never issue nonexclusive licenses, it is sufficient to show that issuing an exclusive license to firm 3 dominates nonexclusive licenses whenever $\rho > \overline{\rho}$. To this end, note that

$$\pi_1^*(n, y, \rho) - \pi_1^*(y, y, \rho) = (1 - \lambda_1) [(3\lambda_1 - 1) (\lambda_1 - \lambda_2) + \rho\lambda_1 (1 - 3\lambda_1 + 3\lambda_2)].$$

If $\lambda_1 \geq 1/3$, the first term inside the square brackets is positive. The second term is also positive if $1-3\lambda_1+3\lambda_2 > 0$. If $1-3\lambda_1+3\lambda_2 < 0$, then $\pi_1^*(n,y,\rho)-\pi_1^*(y,y,\rho)$ is decreasing with ρ, but since it is equal to $(1-\lambda_1)\lambda_2 > 0$ when $\rho = 1$, it follows that $\pi_1^*(n,y,\rho) > \pi_1^*(y,y,\rho)$ for all $\rho \leq 1$. If $\lambda_1 < 1/3$, then the first term inside the square brackets is negative, while the second term is positive and increasing with ρ. Hence, $\pi_1^*(n,y,\rho) > \pi_1^*(y,y,\rho)$ for all $\rho > \overline{\rho}$, where $\overline{\rho} > 0$ since $\lambda_1 < 1/3$ and $\overline{\rho} < 1$ since $\lambda_1 - \lambda_2 < \lambda_1$ and since $1-3\lambda_1 < 1-3\lambda_1+3\lambda_2$.

(ii) To prove that firm 1 will issue an exclusive license to firm 3, I need to show that this option yields a higher expected payoff than all other options. To this end, note that from part (i) of the proof, that $\pi_1^*(n,y,\rho) - \pi_1^*(y,y,\rho)$ if $\lambda_1 < 1/3$ and $\rho > \overline{\rho}$. Moreover, whenever $\lambda_1 < 1/3$,

$$\pi_1^*(n,y,\rho) - \pi_1^*(y,n,\rho) = (1-\lambda_1)(\lambda_2-\lambda_3)(1-3(1-\rho)\lambda_1) > 0.$$

Finally, note that $\pi_1^*(n,y,\rho) - \pi_1(n,n)$ is decreasing with ρ and positive if $\rho < \widehat{\rho}$. ■

Proof of Proposition 6: Absent exclusive licenses, firm 1 faces a choice between issuing nonexclusive licenses and not issuing licences at all. Hence, it is enough to compare $\pi_1^*(y,y)$ and $\pi_1(n,n)$. To this end, note from equations (1) and (10) that $\pi_1(n,n)$ is increasing with λ_1 for all λ_1, while $\pi_1^*(y,y)$ is first increasing with λ_1 when $\lambda_1 < 1/3+2(\lambda_2+\lambda_3)/9$ but then decreasing with λ_1 when $1/3+2(\lambda_2+\lambda_3)/9 < \lambda_1 < 1$. Moreover, $\pi_1^*(y,y) = \pi_1(n,n) \to 0$ when $\lambda_1 \to 0$, $\pi_1^*(y,y) = 0 < \pi_1(n,n)$ when $\lambda_1 \to 1$, and $\frac{\partial \pi_1^*(y,y)}{\partial \lambda_1} > \frac{\partial \pi_1(n,n)}{\partial \lambda_1}$ for λ_1 close to 0. Hence, there exists a unique value of λ_1, denoted, λ_1^{**}, such that $\pi_1^*(y,y) > \pi_1(n,n)$ for all $\lambda_1 < \lambda_1^{**}$ and $\pi_1^*(y,y) < \pi_1(n,n)$ for all $\lambda_1^{**} < \lambda_1 < 1$.

To establish that $\lambda_1^{**} > 1/3$, note that evaluated at $\lambda_1 = 1/3$,

$$\pi_1^*(y,y) - \pi_1(n,n) = \frac{(1-\lambda_2)(1-\lambda_3) - 4\lambda_2\lambda_3}{9} > 0,$$

where the inequality follows because $1/3 = \lambda_1 > \lambda_2 \geq \lambda_3$, so $(1-\lambda_2)(1-\lambda_3) > 4/9$ while $4\lambda_2\lambda_3 < 4/9$. Hence, λ_1^{**} which is attained at the intersection of $\pi_1^*(y,y)$ and $\pi_1(n,n)$ exceeds $1/3$. To compare λ_1^{**} with λ_1^*, recall from Proposition 1 that λ_1^* is defined implicitly by the solution to $\pi_1^*(y,n) = \pi_1(n,n)$. Since $\pi_1^*(y,n) > y_1^*(y,y)$ for all $1/3 < \lambda_1 < 1$ and since both λ_1^* and λ_1^{**} exceed $1/3$, it follows that $\lambda_1^{**} < \lambda_1^*$. ■

Proof of Proposition 8: Suppose that $\lambda_1 < 1/3$. Propositions 1 and 7 imply that under licensing, firm 1 will license its knowledge to both firms 2 and 3 and its expected payoff will be $\pi_1^*(y,y)$, while under selling it will either sell its knowledge to both firms 2 and 3 or will not sell at all, so its expected payoff will be $\max\{\pi^{s*}(y,y), \pi_1(n,n)\}$. The proof of Proposition 1 shows that $\pi_1^*(y,y) > \pi_1(n,n)$ for all $\lambda_1 < 1/3$. Moreover, since $\lambda_1 < 1/3$,

$$\begin{aligned}\pi_1^*(y,y) - \pi_1^{s*}(y,y) &= (1-\lambda_1)^2(3\lambda_1 - \lambda_2 - \lambda_3) - (1-\lambda_1)(2\lambda_1 - \lambda_2 - \lambda_3) \\ &= \lambda_1(1-\lambda_1)(1 - 3\lambda_1 + \lambda_2 + \lambda_3) > 0.\end{aligned}$$

Hence, $\pi_1^*(y,y) > \max\{\pi^{s*}(y,y), \pi_1(n,n)\}$ for all $\lambda_1 < 1/3$, implying that in this range, the best option from firm 1's perspective is to license its knowledge to both firms 2 and 3.

Next, suppose that $1/3 \leq \lambda_1 < 1/2$. Then, Proposition 1 implies that firm 1 will license its knowledge exclusively to firm 2 and will obtain an expected payoff of $\pi_1^*(y,n)$. Under selling, Proposition 7 implies that firm 1 will either sell its knowledge to both firms 2 and 3 or will not sell at all, so its expected payoff will be $\max\{\pi^{s*}(y,y), \pi_1(n,n)\}$. The proof of Proposition 1 shows that $\pi_1^*(y,n) > \pi_1(n,n)$ for all $1/3 \leq \lambda_1 < \lambda_1^*$. Since $\lambda_1^* > 1/(2-\lambda_3) \geq 1/2$, it follows that $\pi_1^*(y,n) > \pi_1(n,n)$ for all $\lambda_1 < 1/2$. Moreover, since $\lambda_1 < 1/2$,

$$\begin{aligned}\pi_1^*(y,n) - \pi_1^{s*}(y,y) &= (1-\lambda_1)(2\lambda_1(1-\lambda_3) - \lambda_2(1-\lambda_1)) - (1-\lambda_1)(2\lambda_1 - \lambda_2 - \lambda_3) \\ &= (1-\lambda_1)\left[\lambda_3(1-2\lambda_1) + \lambda_1\lambda_1\right] > 0.\end{aligned}$$

Hence, $\pi_1^*(y,n) > \max\{\pi^{s*}(y,n), \pi_1(n,n)\}$ for all $\lambda_1 < 1/2$, implying that in this range, firm 1 will prefer to license its knowledge exclusively to firm 2.

Now let $1/2 \leq \lambda_1 < 1/(2-\lambda_3)$. Since $\lambda_1^* \geq 1/(2-\lambda_3)$, Proposition 1 implies that under licensing, firm 1 will licenses its knowledge exclusively to firm 2 and will get an expected payoff of $\pi_1^*(y,n)$. Proposition 7 shows that under selling, firm 1 will prefer to hold on to its technological lead and will get an expected payoff of $\pi_1(n,n)$. The proof of Proposition 1 shows however that $\pi_1^*(y,n) > \pi_1(n,n)$ for all $1/3 < \lambda_1 < \lambda_1^*$. Since $\lambda_1^* \geq 1/(2-\lambda_3)$, it follows that when $1/2 \leq \lambda_1 < 1/(2-\lambda_3)$, firm 1 will prefer to licenses its knowledge exclusively to firm 2.

If $1/(2-\lambda_3) \leq \lambda_1 < \lambda_1^*$, then Proposition 1 shows that under licensing, firm 1 will license its knowledge exclusively to firm 2 and its expected payoff will be $\pi_1^*(y,n)$. Proposition

7 shows that under selling, firm 1 will sell its knowledge exclusively to firm 2 and will get an expected payoff $\pi^{s*}(y,n)$. Now,

$$\begin{aligned}\pi_1^*(y,n)-\pi_1^{s*}(y,n) &= (1-\lambda_1)(2\lambda_1(1-\lambda_3)-\lambda_2(1-\lambda_1))-(\lambda_1(1-\lambda_3)-\lambda_2(1-\lambda_1)) \\ &= \lambda_1\left[1-2\lambda_1)(1-\lambda_3)+\lambda_2(1-\lambda_1)\right].\end{aligned}$$

The sign of this expression depends on the square bracketed term, which is decreasing with λ_1 and hence is minimized at $1/(2-\lambda_3)$. Evaluated at $\lambda_1=1/(2-\lambda_3)$, the square bracketed term becomes $\frac{(\lambda_2-\lambda_3)(1-\lambda_3)}{2-\lambda_3}>0$. Hence, $\pi_1^*(y,n)>\pi^{s*}(y,n)$ for all $\lambda_1\geq 1/(2-\lambda_3)$, implying that whenever $1/(2-\lambda_3)\leq\lambda_1<\lambda_1^*$, firm 1 will prefer to license its knowledge exclusively to firm 2.

Finally, suppose that $\lambda_1\geq\lambda_1^*$. Proposition 1 shows that under licensing, firm 1 will prefer to hold on to its technological lead, so its expected payoff will be $\pi_1(n,n)$. Proposition 7 shows that under selling, firm 1 will prefer to sell its knowledge exclusively to firm 2, so its expected payoff will be $\pi^{s*}(y,n)$. Proposition 7 reveals that $\pi^{s*}(y,n)>\pi_1(n,n)$ for all $\lambda_1>1/(2-\lambda_3)$. Since $\lambda_1^*>1/(2-\lambda_3)$, it follows that $\pi^{s*}(y,n)>\pi_1(n,n)$, for all $\lambda_1\geq\lambda_1^*$, implying that firm 1 will prefer to sell its knowledge exclusively to firm 2. ■

Proof of Proposition 10: To determine which unilateral licensing agreements maximize the joint payoff of the three firms, note that the joint expected payoffs of the three firms when firm 1 issues nonexclusive licenses to firms 2 and 3 is given by:

$$\begin{aligned}\widetilde{\Pi}_1(y,y) &= \lambda_1\left(1-\widetilde{\lambda}_{21}\right)\left(1-\widetilde{\lambda}_{31}\right)+\widetilde{\lambda}_{21}(1-\lambda_1)\left(1-\widetilde{\lambda}_{31}\right)+\widetilde{\lambda}_{31}(1-\lambda_1)\left(1-\widetilde{\lambda}_{21}\right) \\ &= \delta_1^2\left[\delta_2+\delta_3+\delta_2\delta_3(1-3\delta_1)\right].\end{aligned}$$

The joint expected payoffs when firms 2 and 3 issues nonexclusive licenses, $\widetilde{\Pi}_2(y,y)$ and $\widetilde{\Pi}_3(y,y)$, are analogous.

Now note that

$$\widetilde{\Pi}_1(y,y)-\widetilde{\Pi}_2(y,y)=3(\delta_2-\delta_1)\delta_1\delta_2\delta_3\left[\delta_1+\delta_2-H\right],$$

$$\widetilde{\Pi}_1(y,y)-\widetilde{\Pi}_3(y,y)=3(\delta_3-\delta_1)\delta_1\delta_2\delta_3\left[\delta_1+\delta_3-H\right],$$

and

$$\widetilde{\Pi}_2(y,y)-\widetilde{\Pi}_3(y,y)=3(\delta_3-\delta_2)\delta_1\delta_2\delta_3\left[\delta_2+\delta_3-H\right],$$

where H is defined in the proposition. Recalling that $\lambda_1 > \lambda_2 \geq \lambda_3$, it follows that $\delta_1 < \delta_2 \leq \delta_3$. Hence, $\delta_1 + \delta_2 < \delta_2 + \delta_3 \leq \delta_2 + \delta_3$. Moreover, H is a decreasing function of δ_1, δ_2, and δ_3 and is equal to 4/3 when δ_1, δ_2 and δ_3 approach 1. Hence, there are three possible cases:

(i) $\delta_1 + \delta_2 > H$. Then $\widetilde{\Pi}_1(y, y) > \widetilde{\Pi}_2(y, y)$. Moreover, since $\delta_3 \geq \delta_2$, then $\widetilde{\Pi}_1(y, y) > \widetilde{\Pi}_3(y, y)$. Hence, the aggregate expected payoffs are largest when firm 1 issues nonexclusive licenses.

(ii) $\delta_1 + \delta_2 < H < \delta_2 + \delta_3$. Then $\widetilde{\Pi}_2(y, y) > \widetilde{\Pi}_1(y, y)$ and $\widetilde{\Pi}_2(y, y) > \widetilde{\Pi}_3(y, y)$, so the aggregate expected payoffs are largest when firm 2 issues nonexclusive licenses.

(iii) $\delta_2 + \delta_3 < H$. Then $\widetilde{\Pi}_3(y, y) > \widetilde{\Pi}_2(y, y)$. Moreover, since $\delta_2 \geq \delta_1$, then $\widetilde{\Pi}_3(y, y) > \widetilde{\Pi}_1(y, y)$. Hence, the aggregate expected payoffs are largest when firm 3 issues nonexclusive licenses. ■

9 References

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