Bargaining and Sharing Innovative Knowledge*

Claude d'Aspremont[†], Sudipto Bhattacharya[‡] and Louis-André Gérard-Varet[§]

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Abstract

We consider the problem of bargaining over the disclosure of interim research knowledge between two participants in an R&D race for an ultimate, patentable invention. Licence fee schedules that are functions of the "amount of knowledge disclosed", by the leading to the lagging agent, are examined for their abilities to attain efficient outcomes and varying shares of the surplus arising from disclosure. In her sequential-offers bargaining games, the uninformed buyer is able to elicit full disclosures without sharing the incremental surplus with any type of the licensor, and thus do as well as a perfectly informed and discriminating knowledge licensee.

1 Introduction

An important feature of cooperation between firms in Research and Development (R & D) is the exchange of the knowledge that they possess either before the completion of innovative activity, or after, when new marketable products have been created. However, the institutional setting in which such exchanges should take place is difficult to establish. In particular, the questionable adequacy of the (Walrasian) market mechanism in organizing efficiently such exchanges is not

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†CORE, Université catholique de Louvain

‡LSE and CEPR

§GREQAM and UMR-NRS

simply due to the usually small number of participants, but also to the specificities of knowledge as a commodity. As stressed by Arrow (1993), "knowledge is a hard commodity to appropriate, and it is socially inefficient to appropriate it".

We focus here on "interim knowledge", that is, a kind of basic research knowledge which can be appropriated by some firm, but which could at the same time be shared with another one so as to increase, in the R&D process, the aggregate chances for some ultimate invention leading to commercial payoffs. In the situation we consider, there are two competing laboratories, each owned by a different firm, and each trying to develop an innovation that would give to its owner-firm a decisive advantage in the product market, *e.g.* imagine two pharmaceutical firms competing for discovering and commercialising a new drug, or two chemical firms competing for a new cost-reducing process. One laboratory will be assumed to have a superior (Blackwell-ordered) level of basic research knowledge, and thus be capable of inventing the final product or technology with higher probability over a given time-span.

Superior knowledge of the informed firm is to be thought of as an amount of technological know-how that is partially or fully transferable to the uninformed firm. Wether this knowledge is hared or not, externalities are prevailing, since both firms are competing for the first invention. Moreover, these externalities can be modified: if a more knowledgeable firm transfers some of its knowledge (and it cannot transfer more than it has) to a less knowledgeable one then the chances to discover first are lower for the former, but greater for the latter, and aggregate prospects for discovery are enhanced. In such a "patent race" framework, with few actors, and well-defined property rights but important externalities, it seems natural to look for an institutional setting that leads to efficient allocational outcomes, in particular via bargaining over enforceable *licence fee contracts* that would result in knowledge sharing agreements across firms. In the following, we shall argue in favour of licence fee contracts that are *contingent on invention* by the licensee.

We shall examine the above scenario in two different ways. The first approach will be static and use the abstract framework of direct mechanism design, whereby an informed firm may disclose, more or less fully, its private knowledge. This determines the amounts of knowledge to be shared, as well as the probabilities of agreeing on an associated licence fee. Our purpose is to characterize a class of efficient and implementable direct bargaining mechanisms, assuming that the licence fee paid by the licensee is contingent on its own first invention (making the earlier knowledge transfer more easily verifiable by a court and the money transfer more easily payable by the licensee). Our second approach consists of investigating the possibility of obtaining a subset of such efficient direct mechanisms as the equilibrium outcomes of sequential noncooperative bargaining games, taking into account the asymmetry of information between the participants in the bargaining (and R&D) process.

In both these approaches to bargaining, three main features of our model will be shown to characterize the negotiations, and underpin the conclusions. The first important feature is that the standard *Spence-Mirrlees single-crossing property cannot hold* in our model, due to the combination of two different effects of higher knowledge disclosure: a gain resulting from a higher licence fee,[1] but also a loss of competitive advantage in subsequent R&D for the disclosing firm. This combination implies the non-concavity of the informed firm's payoffs *vis-a-vis* disclosure and leads to extremal disclosure solutions, rather than interior optimal partial disclosures. The second important feature is the *knowledge-dependent feasible disclosure set* for the informed firm, that is, the assumed infeasibility for the informed firm to disclose more interim knowledge that it has.[2] The third is the *knowledge-dependent outside option* available to each firm, which consists of having each laboratory using only its own initial level of basic knowledge in further R&D, with probabilities of (first) invention depending only on both firms' *a priori* knowledge levels. These three main features, the union of which is specific to our model, lead to our main conclusions: the extremal outcome that will prevail is exactly full disclosure and it may, in some cases, involve no surplus relative to its outside option for the licensor.

These features account for important differences with respect to the literature. For instance, in contrast to the literature on bargaining under incomplete information *over private goods*

[1] This is standard as a result on quality disclosure (see, *e.g.* Milgrom (1981)).

[2] Following Okuno-Fujiwara, Postlewaite and Suzumura (1990), we could say that firm 1 is allowed to transmit to firm 2 only "certifiable" reports. However, their viewpoint is somewhat different from our mechanism design perspective since, for a given game (*i.e.* a given mechanism), they investigate how the asymmetry of information can be eliminated by a first stage of communication.

(as reviewed by Wilson (1987) and by Kennan and Wilson (1993)), we obtain an "anti-Coase property", in the sense that if the non-informed agent (the monopolist seller of a durable good in Coase (1972)) makes the pricing proposals, regarding knowledge disclosure and licensing fees, it is this agent who will capture the *whole* incremental surplus from (full) disclosure, and *not* the informed seller (the customer in Coase's case), who will nevertheless be induced to reveal all its knowledge! Our conclusions will also stand in contrast with recent work studying common value (but still private good) bargaining problems under incomplete information (*e.g.* Evans (1989) and Vincent (1989)). In particular, equilibrium agreement in sequential-offer(s) bargaining need not involve any delay in our model. Our environment of bargaining, over an *excludable public good* (knowledge), is the source of these differences.[3]

Other papers, notably by Green and Scotchmer (1995) and Aghion and Tirole (1994), dealing with multi-stage patent races and with R&D knowledge-selling arrangements respectively, also analyse the problem of dividing the expected surplus from ultimate R&D success among generators and utilizers of disclosed interim research knowledge. In essence, their approach is to consider interim bargaining solutions between these two agents, subsequent to the realization of such knowledge, in a complete-information (Rubinstein (1982)) framework. In both these papers, the problem of bargaining over transfers of such innovative knowledge is considerably simplified, by assuming that the informed agent who generates basic knowledge is *unable* to develop it further into a marketable invention, whereas the uninformed agent who can do such development work was incapable of having generated basic knowledge. In our model, disclosed

[3]The literature on trading procedures with externalities, such as Muto (1986), or more recently Jehiel and Moldovanu (1995), deals only with complete information bargaining. See also Imai (1994) on bilateral bargaining under complete information about the licensing of a new production technology, whose cost is common knowledge, that is subject to the (off-equilibrium) threat of *imitation*, under imperfect patent protection for the first inventor. Both a public good dimension and incomplete information are present in Bhattacharya, Glazer and Sappington (1990, 1992) and d'Aspremont, Bhattacharya and Gérard-Varet (1998), who characterize optimal incentive (transfer) schemes for the sharing of knowledge before a second stage where success probabilities are functions of the agents' efforts. But their point of view is that of a disinterested planner designing the appropriate disclosure- and invention-contingent transfers, that result in full knowledge disclosure and first-best efficient effort choices.

interim research knowledge can be used *simultaneously* by multiple participants in an ongoing R&D race, and thus it has an important excludable public good aspect.[4]

The paper is organized as follows. In Section 2 we describe our model of licensing the disclosure of interim research knowledge in a R&D race context, and introduce the notion of static direct bargaining mechanisms. In Section 3, we first characterize a class of (first-best) efficient direct bargaining mechanisms satisfying both incentive compatibility and individual rationality conditions, and then explore the issue of implementing a subset of such efficient static mechanisms (outcomes) as sequential equilibria of infinite-horizon sequential bargaining games, having asymmetric information about the informed agent's type (*i.e.* level of knowledge). In Section 4, we conclude.

2 Knowledge, disclosure, and bargaining mechanisms

2.1 The R&D race model

We consider a model with two firms, each having its own research laboratory. Both firms consider some specific R&D activity aiming at the *same* ultimate invention, of value V, which is completely appropriable by the first inventor (through patent protection). The stochastic process describing the research activity of each firm is assumed, for simplicity, to be of the Poisson type, with statistically independent successes for the two firms conditional on their knowledge levels.[5] In particular, the possibility of tied inventions, and the resulting competition

[4] See also Denicolo (1998) for the implementation of a similar distinction in the context of multi-stage patent races.

[5] See *e.g.* Loury (1979), Dasgupta and Stiglitz (1980), Bhattacharya and Ritter (1983). As explained in this last reference, such a process of R&D may be seen as investigating sequentially a countably infinite number of techniques, each represented as a Bernoulli random variable, taking the value 1 (success) with some probability, and the value 0 (failure) with the complementary probability. The knowledge of a firm determines the (finite) rate at which it eliminates techniques by testing. The idea is to consider the limiting distribution of the time to first-invention as the rate of testing techniques becomes large.

at the production stage, may be neglected.[6]

One firm, firm 1, is known to possess private knowledge which is valuable in its research and, if disclosed, in the research of its competitor, firm 2. The level of knowledge of firm 1, determining its type, is here represented by its Poisson intensity of invention, denoted by $\lambda > 0$. From the point of view of an outside observer, or of the competitor, firm 1's state of knowledge is a random variable distributed according to some probability law which is common knowledge and with support $[\underline{\lambda}, \overline{\lambda}]$. Firm 2's state of knowledge, which is commonly known, is given by $\mu \leq \underline{\lambda}$, with μ being its own Poisson intensity of invention.[7] Knowledge can be communicated or transferred, partially or fully, by the informed agent through the disclosure of technological information of direct usefulness to its competitor, who can then (and only then) augment its own Poisson intensity parameter.[8]

First, let us describe the R&D game resulting from firm 1 *not* disclosing any of its knowledge to firm 2; this will determine these firms' *outside options* in their bargaining over knowledge licensing. Both agents share a common discount rate δ in continuous time. Only one of the two firms, the first inventor, will obtain V, the privately appropriable value of ultimate invention. The conditional probability that firm 1 (the informed player) of type λ is the first inventor is $\lambda/(\lambda+\mu)$, and $\{1-e^{-(\lambda+\mu)t}\}$ is the exponential cumulative distribution function for time t of the first invention. The discounted expected payoff of firm 1 of type λ in the no-disclosure situation is thus given by

[6] This is because we have a continuous-time invention race model. A one-shot invention (or contest) model is more complex. The possibility of ties would require us to specify the type of competition of the productive stage. We shall discuss this case briefly below for the situation where competition is of the Bertrand type, implying that the value V is lost in case of tied inventions, in the absence of "exclusive" interim knowledge-licensing contracts.

[7] In the bargaining literature, the case $\mu < \underline{\lambda}$ is called the "gap" case, the case $\mu = \underline{\lambda}$ the "no-gap" case (see *e.g.* Fudenberg and Tirole (1992, chap. 10)). In our analysis the two cases can be treated simultaneously, with similar results.

[8] In other words, it is not enough that firm 2 knows the (interval of) value(s) of the parameter denoting the intensity of invention of firm 1. To get knowledge transferred, voluntary disclosure, of its technical content, is required. Both *a priori* and disclosed knowledge levels could be thought of as (the resulting) rates for testing of alternative techniques for the desired invention; see Bhattacharya and Ritter (1983).

$$L_1^0(\mu,\lambda) = \int_0^\infty Ve^{-\delta t}\left(\frac{\lambda}{\lambda+\mu}\right)\frac{d}{dt}\{1-e^{-(\lambda+\mu)t}\}dt = \frac{\lambda V}{\lambda+\mu+\delta}. \tag{2.1}$$

The discounted expected payoff of firm 2 (the uninformed player), in the no-disclosure situation, is obtained after replacing $\lambda/(\lambda/\mu)$ with $\mu/(\lambda+\mu)$, which is the conditional probability that firm 2 is the first inventor in case that firm 1 is of type λ, and taking expectations with respect to the commonly known distribution on λ (this expectation operator is denoted $E_\lambda[\cdot]$). We obtain

$$E_\lambda[L_2^0(\mu,\lambda)] = E_\lambda\left[\frac{\mu V}{\lambda+\mu+\delta}\right]. \tag{2.2}$$

Note that the λ-contingent payoffs to be anticipated in the absence of knowledge sharing would play the roles of the firms' outside options in the bargaining phase to be described next, and are affected by both parameters: μ which is common knowledge and λ which is asymmetrically known.[9] For simplicity we set $V = 1$.

2.2 Direct bargaining mechanisms for knowledge licensing

To describe the bargaining phase, we employ, in this section, the abstract approach to bargaining as formulated through direct mechanism design, along the lines of Myerson (1979), Myerson-Satterthwaite (1983), and also by Chatterjee-Samuelson (1983). To define a "direct bargaining mechanism" we need two ingredients. First we need to define what is an *outcome* of the bargaining between the informed firm 1 and the uninformed firm 2. This is given by the disclosed knowledge $Din[\mu,\tilde{\lambda}]$ to the uninformed, and by some "probability of agreement" $P \in [0,1]$. The second ingredient is a *disclosure-contingent licence fee schedule*, that is a function $f : [\mu,\tilde{\lambda}] \to [0,1]$. With $D \in [\mu,\tilde{\lambda}]$ the amount of knowledge disclosed by firm 1, the licence fee $f(D) \in [0,1]$, a proportion of $V = 1$, is the price to be paid by the licensee, the uninformed firm 2, to the licensor, the informed firm 1, if and only if the licensee invents first in the R&D race. We naturally assume that $f(\mu) = 0$.

[9] This feature is absent in the Vincent (1989) model of bargaining with common values, in which the seller's valuation $\tilde{S}$ is privately known and the buyer's valuation is $B = \tilde{S}+\theta$, where $\theta > 0$ is common knowledge and the buyer's outside option payoff is zero. In our model, the two agents' discounted expected payoffs are negatively affiliated (*via* λ).

If disclosing, a firm of type λ is assumed to be able to disclose only knowledge levels D such that $\mu \leq D \leq \lambda$; that its D is not allowed to exceed its λ can be justified by noting that firm 1 cannot pretend (to firm 2) to have more knowledge that it has, by the very nature of technical knowledge. If it would pretend, this could be easily detected.[10] We also assume that the time and ownership of first invention is verifiable, and that any disclosure cum licensing contract is enforceable conditional on the first invention; post-invention, D is verifiable as well as observable.[11]

Given that the licensing fees are determined by the schedule $f(D)$, we denote the discounted expected payoff of the λ-type agent, when disclosing D, as

$$L_1(D, \lambda, f(D)) = \left(\frac{\lambda}{\lambda + D + \delta}\right) + \left(\frac{Df(D)}{\lambda + D + \delta}\right) = \frac{\lambda}{\lambda + D + \delta}\left(1 + \frac{DF(D)}{\lambda}\right). \tag{2.3}$$

Similarly, the discounted expected payoff of the uninformed agent, the licensee, when a type λ licensor discloses D, is denoted by

$$L_2(D, \lambda, f(D)) = \frac{D}{\lambda + D + \delta}(1 - f(D)). \tag{2.4}$$

Equations (2.3) and (2.4) are derived using methods analogous to those in equations (2.1) and (2.2) above.

We wish to note here that a static description of the bargaining procedure, where negotiation

[10]For example, the technique testing rate, or the error probability in clinical trials, of new technical knowledge could be readily discerned in synthetic samples. Also, the fact that disclosure is submitted to the feasibility constraint $D \leq \lambda$ (a type-dependent constraint) is no problem for the application of the Revelation Principle. As also shown by Green and Laffont (1986), this is linked to a "nested range" property, trivially satisfied in our case since, for any λ_1, λ_2 and λ_3 in $[\underline{\lambda}, \overline{\lambda}]$, if $\lambda_2 \leq \lambda_1$ and $\lambda_3 \leq \lambda_2$ then $\lambda_3 \leq \lambda_1$.

[11]If disclosure-contingent licence fees, paid if and only if the licensee invents, are to be implementable, the quality of interim knowledge disclosed must be verifiable to a third-party (*e.g.* a court) at time of first invention. We could have assumed that the uninformed firm has resources to pay the licensor if and only if it ultimately invents and patents, obtaining a positive product market payoff. Note that making the licence fee f depend on D, rather than on the claimed type $\hat{\lambda}$ (of firm 1) directly, is without loss of generality for incentive compatible mechanisms (if $\lambda' \neq \hat{\lambda}$, but $D(\hat{\lambda})$ and $f(\hat{\lambda}) > f(\lambda')$, then claiming one's type to be $\hat{\lambda}$ would dominate the alternative claim of λ').

is supposed to take place instantaneously, can be viewed as an abstract depiction of a more concrete sequential procedure where multiple rounds of negotiations would be authorised.

The scenario we will focus on, that may be called the "pre R&D bargaining scenario", supposes that the R&D activity of each laboratory is only started after the licensing negotiation is over. It implies, for n negotiation rounds each of length $\Delta > 0$, that $Pe^{-\delta n\Delta}$ and, respectively for firms 1 and 2,

$$
\begin{aligned}
U_1(D, \lambda; P, f) &\equiv P\, L_1(D, \lambda, f(D)), && (2.5)\\
E_\lambda[U_2(D, \lambda; P, f)] &\equiv E_\lambda[P\, L_2(D, \lambda, f(D))]. && (2.6)
\end{aligned}
$$

These formulas can be used in the present static framework, taking $P = P(\hat{\lambda})$, as a function of $\hat{\lambda}$, the type claimed by firm 1, to be, together with $D(\hat{\lambda})$ and $f(D)$, ingredients of the outcome function.[12]

Then an *efficient outcome function* can be directly defined in terms of these payoffs. It is defined as the solution $(D^*, P^*) : [\underline{\lambda}, \overline{\lambda}] \to [\mu, \overline{\lambda}] \times [0, 1]$, to the problem

$$\max_{D \in [\mu, \overline{\lambda}], P \in [0,1]} [U_1(D, \lambda; P, f) + U_2(D, \lambda; P, f)],$$

[12] An alternative scenario, that may be called the "ongoing-R&D scenario", is to suppose that the laboratory of each firm is involved in R&D activity while negotiations go on. First invention by some firm could occur during some round of negotiation, stopping the process immediately before any disclosure has been made. Formally, the total discounted expected utility of firm 1, when n negotiation rounds each of length $\Delta > 0$ are required for agreement, can be computed as follows

$$
\begin{aligned}
U_1 &= \int_0^{n\Delta} e^{-\delta t} \left(\frac{\lambda}{\lambda + \mu}\right) \frac{d}{dt}\{1 - e^{-(\lambda+\mu)t}\} dt + e^{-(\lambda+\mu)n\Delta} e^{-\delta n\Delta} L_1(D, \lambda, f(D)\\
&= (1 - e^{-(\lambda+\mu)n\Delta} e^{-\delta n\Delta}) L_1^0(\mu, \lambda) + e^{-(\lambda+\mu)n\Delta} e^{-\delta n\Delta} L_1(D, \lambda, f(D)).
\end{aligned}
$$

Or, letting $P = e^{-\delta n\Delta}$ and $\pi = e^{-(\lambda+\mu)n\Delta}$, $U_1(D, \lambda; P, f) \equiv (1 - \pi P)L_1^0 + \pi P L_1(D, \lambda, f(D))$. Both P and π, through the dependence of n (the number of negotiation rounds) on the type $\hat{\lambda}$ claimed by firm 1, can be functions of $\hat{\lambda}$. Also, $P = 1$ and $\pi = 1$ if and only if $n(\hat{\lambda}) = 0$. Analogous computations for firm 2 give $E_\lambda[U_2(D, \lambda; P, f)] \equiv E_\lambda[(1 - \pi P)_2^0 + \pi P L_2^0(D, \lambda, f(D))]$.

Note that π should not be taken as a separate ingredient of the outcome function, since it is linked to P, through their joint dependence on $n(\hat{\lambda})$.

under the constraint that $D(\lambda) \leq \lambda$, $\forall\, \lambda \in [\underline{\lambda}, \overline{\lambda}]$. This is equivalent to maximizing, with respect to the variables D and P and under the same constraint, the function[13]

$$P\left[\frac{\lambda + D}{\lambda + D + \delta}\right].$$

The solution clearly requires *full-disclosure* and *sure-agreement*

$$D(\lambda) = \lambda, \quad P^*(\lambda) = 1, \quad \forall\, \lambda \in [\underline{\lambda}, \overline{\lambda}]. \tag{EF}$$

But then notice that with $P = \mathbf{1}$, resulting from $n(\hat{\lambda}) = 0$, for all $\lambda \in [\underline{\lambda}, \overline{\lambda}]$, in the multiple-round bargaining,

$$U_i(D, \lambda; 1, f) \equiv L_i(D, \lambda, f(D)), \quad i = 1, 2.$$

This fixes the first part, namely the outcome functions, of the efficient direct bargaining mechanisms we wish to look at.[14] To complete the characterization, one needs now to examine the transfer functions (disclosure-contingent licence fee schedules) $f : [\mu, \overline{\lambda}] \to [0, 1]$ that implements (a subset of) such efficient mechanisms. Two requirements need to be imposed on agents' choices. First, the truthful revelation strategy, $\hat{\lambda} = \lambda$, leading to $D^*(\lambda) = \lambda$, $\forall\, \lambda \in [\underline{\lambda}, \overline{\lambda}]$, which implements the full disclosure required by efficiency, should be privately optimal for each informed agent, *i.e.* the efficient bargaining mechanism determined by f should be *incentive compatible*. That is, we must have

$$L_1(\lambda, \lambda, f(\lambda)) \geq L_1(D, \lambda, f(D)), \quad \forall\; D \in [\mu, \lambda], \forall\, \lambda \in [\underline{\lambda}, \overline{\lambda}]. \tag{IC}$$

Second, among efficient mechanisms which are incentive compatible, and hence fully separating, we must consider only those satisfying *ex post individual rationality* in the sense that

$$L_1(\lambda, \lambda, f(\lambda)) \geq L_1^0(\mu, \lambda), \quad L_2(\lambda, \lambda, f(\lambda)) \geq L_2^0(\mu, \lambda), \quad \forall\, \lambda \in [\lambda, \overline{\lambda}]. \tag{IR}$$

These two conditions ensure that each firm prefers (at least weakly) sure-agreement and full disclosure, to partial disclosure or to its outside option of isolated research, with no knowledge sharing.[15] We examine these conditions further in what follows.

[13] In the ongoing-research case, this function is $\{(\lambda + \mu)/(\lambda + \mu + \delta) + \pi P[(D - \mu)/(\lambda + D + \delta)]\}$, and it also leads to full-disclosure and sure-agreement *with* $\pi((\lambda, \hat{\lambda}) = 1$, for all $\lambda \in [\underline{\lambda}, \overline{\lambda}]$.

[14] The same conclusion holds in the ongoing-research scenario since $\pi \equiv 1$.

[15] Without assuming efficiency, individual rationality constraints are different in the two scenarios. In the

3 Bargaining and equilibrium surplus-sharing

3.1 An implementation result for efficient direct bargaining mechanisms

We now characterize efficient direct bargaining mechanisms satisfying both incentive compatibility and individual rationality, in a specific subset of all direct bargaining knowledge-licensing mechanisms. For that purpose, we introduce a class of twice continuously differentiable fee schedules, denoted $f_\alpha : [\mu, \overline{\lambda}] \to [0,1]$, satisfying $\forall \lambda \in [\underline{\lambda}, \overline{\lambda}]$,

$$L_1(\lambda, \lambda, f_\alpha(\lambda)) = L_1^0(\mu, \lambda) + \alpha[L_1(\lambda, \lambda, f_\alpha(\lambda)) + L_2(\lambda, \lambda, f_\alpha(\lambda)) - L_1^0(\mu, \lambda) - L_2^0(\mu, \lambda)], \quad (3.1)$$

where $\alpha \in [0,1]$ is the proportion of the *incremental* surplus from full disclosure attributed to the licensor, *i.e.* the informed firm 1, if its knowledge is fully disclosed to the competing firm 2. We thus define a family (f_α) of fee schedules, where f_0 is zero-surplus (relative to the outside option) for all types of the informed licensor, and f_1 is zero-surplus for the licensee. It is easily seen, using (2.1)–(2.4), that the α-schedule f_α defined by analytic extension of (3.1) to the whole interval $[\mu, \overline{\lambda}]$ satisfies

$$\forall\, D \in [\mu, \overline{\lambda}], D f_\alpha(D) = D(2\alpha - 1) + \frac{[(1-\alpha)D - \alpha\mu]}{(D + \mu + \delta)}(2D + \delta). \quad (3.2)$$

In particular one gets: $\forall\, D \in [\mu, \overline{\lambda}]$,

$$f_0(D) = \frac{2D + \delta}{(D + \mu + \delta)} - 1, \quad (3.3)$$

$$f_1(D) = 1 - \frac{\mu(2D + \delta)}{D(D + \mu + \delta)}. \quad (3.4)$$

The following key proposition gives a surprisingly general existence result for efficient, incentive compatible, and individually rational direct bargaining mechanisms in our model of knowledge sharing *via* licensing.

ongoing-R&D case, we require the same condition as above, whereas in the other case the condition becomes $P\, L_i(D(\lambda), \lambda, f(D(\lambda))) \geq L_i^0(\mu, \lambda), i = 1, 2$, where $D(\lambda)$ maximizes U_1 in (2.5) given $f(D)$. In essence the outside options, $L_i^0(\mu, \lambda)$, are also flow disagreement payoffs in the ongoing-R&D case, but not in the other one (given anticipated bargaining agreement in n rounds).

Proposition 1 *For any $\alpha \in [0,1]$ the direct bargaining mechanism defined by sure-agreement and full knowledge disclosure (i.e. $D^*(\lambda) = \lambda, P^*(\lambda) = 1, \forall\, \lambda \in [\underline{\lambda}, \overline{\lambda}]$), together with the fee schedule f_α, is efficient (EF), incentive compatible (IC) and individually rational (IR).*

Before proving Proposition 1, we derive from (2.3) two basic results about the informed agent's payoff function. The first lemma shows that in this model, the classical Spence-Mirlees single-crossing property does *not* hold.[16] Let, for all $(D, \lambda, x) \in \langle[\mu, \overline{\lambda}] \times [\underline{\lambda}, \overline{\lambda}] \times [0,1]\rangle$ and $f(D) = x$

$$\overline{L}_1(D, \lambda, x) \equiv L_1(D, \lambda, f(D) = x) = \frac{\lambda + Dx}{\lambda + D + \delta}. \tag{3.5}$$

Clearly,

$$\frac{\partial \overline{L}_1}{\partial x} > 0 \text{ and } \frac{\partial \overline{L}_1}{\partial \lambda} > 0.$$

We have the following intermediate result.

Lemma 1 *The marginal rate of substitution $[dx/dD]_{\overline{L}_1}$, computed in the (D, x) space along any indifference curve of the payoff function $\overline{L}_1(D, \lambda, x)$, is increasing in λ.*

Proof: Since

$$\frac{\partial \overline{L}_1}{\partial D} = \frac{(\lambda + \delta)x - \lambda}{(\lambda + D + \delta)^2} \text{ and } \frac{\partial \overline{L}_1}{\partial x} = \frac{D}{\lambda + D + \delta},$$

we easily get

$$\begin{aligned}
\frac{\partial}{\partial \lambda}\left[\frac{dx}{dD}\right]_{\overline{L}_1} &= \frac{\partial}{\partial \lambda}\left[-\frac{\partial \overline{L}_1/\partial D}{\partial \overline{L}_1/\partial x}\right] = \frac{\partial}{\partial \lambda}\left[-\frac{(\lambda + \delta)x - \lambda}{D(\lambda + D + \delta)}\right] \\
&= \left[\frac{(1-x)}{D(\lambda + D + \delta)}\right] + \left[\frac{x(\lambda + \delta) - \lambda}{D(\lambda + D + \delta)^2}\right] \\
&= \left[\frac{D(1-x) + \delta}{D(\lambda + D + \delta)^2}\right] > 0
\end{aligned}$$

because, with $x \in [0,1]$ and $\delta > 0$, $(D(1-x) + \delta) > 0$. ■

[16] For an analysis of Spence-Mirrlees and other (more general) single-crossing properties, see Milgrom and Shannon (1994).

Building upon this particular feature of our model, our second lemma shows that, unlike in usual signalling or mechanism design models, there is a "reverse monotonicity" of any schedule $D(\lambda)$ of interior maximal choices. In other words, obtaining any disclosure choice schedule $D(\lambda)$, which is monotone increasing in λ, as a set of *interior* maximal choices, is just impossible in our model.

Lemma 2 *Consider any twice-continuously differentiable fee function f and, for $\lambda' \in [\underline{\lambda}, \overline{\lambda}]$, let $D' \in [\mu, \overline{\lambda}]$ be an interior critical point w.r.t. D of $L_1(D, \lambda', f(D))$, taken as a function of D both directly and via $f(D)$, also satisfying*

$$\frac{\partial^2}{\partial D^2} L_1(D', \lambda', f(D')) \neq 0. \tag{3.6}$$

Then, for all λ in a neighbourhood of λ', there exists a continuously differentiable function $D(\lambda)$ such that $(\partial/\partial D)L_1(D(\lambda), \lambda, f(D(\lambda))) = 0$ in this neighbourhood, and $D(\lambda)$ is an interior minimum (resp. maximum) as

$$\frac{dD(\lambda)}{d\lambda} > 0 \ (\textit{resp.} \ < 0).$$

Proof: For any continuously differentiable function $D(\cdot)$ satisfying

$$\frac{D}{\partial D} L_1(D(\lambda), \lambda, f(D(\lambda))) = 0$$

in a neighbourhood of λ' (under (3.6), such a function exists by the Implicit Function Theorem), we get by differentiating

$$\frac{dD}{d\lambda} = -\frac{\dfrac{\partial^2}{\partial\lambda\partial D} L_1(D(\lambda), \lambda, f(D(\lambda)))}{\dfrac{\partial^2}{\partial D^2} L_1(D(\lambda), \lambda, f(D(\lambda)))}. \tag{3.7}$$

Since, using (3.5), $[\partial L_1/\partial D] = [\partial \overline{L}_1/\partial D] + [\partial \overline{L}_1/\partial x][\partial f/\partial D]$, we have

$$\frac{\partial L_1/\partial D}{\partial \overline{L}_1/\partial x} = \frac{\partial \overline{L}_1/\partial D}{\partial L_1/\partial x} + [\partial f/\partial D].$$

Hence, we get for $D = D(\lambda)$ and any λ in the chose neighbourhood of λ',

$$\begin{aligned} \frac{\partial}{\partial\lambda}\left[\frac{\partial \overline{L}_1/\partial D}{\partial \overline{L}_1/\partial x}\right] &= \frac{1}{(\partial \overline{L}_1/\partial x)^2}\left[\frac{\partial^2 L_1(D, \lambda, \lambda, f(D))}{\partial\lambda\partial D}\frac{\partial \overline{L}_1}{\partial x} - \frac{\partial^2 \overline{L}_1}{\partial\lambda\partial x}\frac{\partial L_1(D, \lambda, f(D))}{\partial D}\right]_{D=D(\lambda)} \\ &= \frac{1}{(\partial \overline{L}_1/\partial x)^2}\left[\frac{\partial^2 L_1(D, \lambda, d(D))}{\partial\lambda\partial D}\frac{\partial \overline{L}_1}{\partial x}\right]_{D=D(\lambda)} < 0, \end{aligned}$$

by Lemma 1 above. Therefore, using equation (3.7), in this neighbourhood, $dD(\lambda)/d\lambda > 0$ if and only if

$$\frac{\partial^2}{\partial D^2} L_1(D(\lambda), \lambda, f(D(\lambda))) > 0.$$

and *vice-versa*. ■

Figure 1 illustrates the idea underlying Proposition 1, for three types $\lambda_1 > \lambda_2 > \lambda_2$. The failure of the Spence-Mirrlees property (Lemma 1) makes it feasible to have $[L_1(\lambda_3, \lambda_2, f_0) - L_1(\mu, \lambda_2)] < 0$, even though $L_1(\lambda_3, \lambda_3, f_0) = L_1(\mu, \lambda_3)$. Moreover, the infeasibility of "more than full knowledge disclosure", $D(\lambda) \leq \lambda$, implies that type λ_2 cannot obtain more than $L_1(\mu, \lambda_2)$ under $f_0(D)$, by choosing $D \in (\lambda_2, \lambda_1]$.

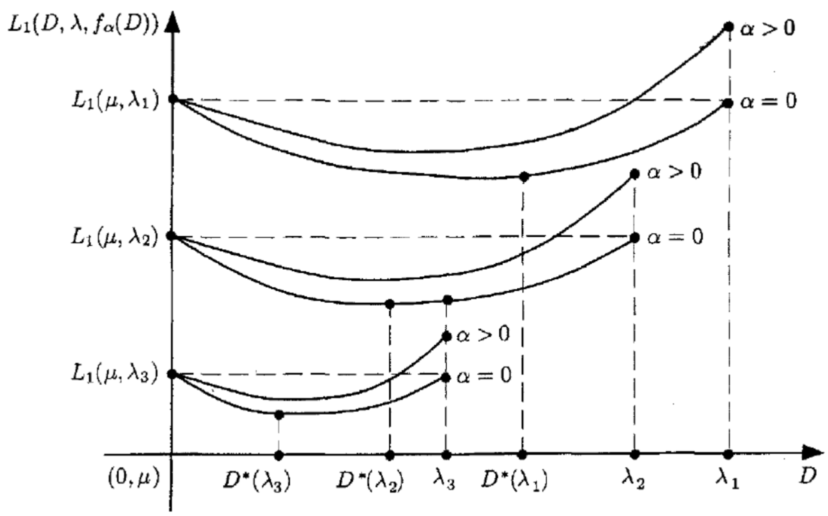

FIGURE 1

To get a further intuition behind Proposition 1, outside our Poisson race model in which tied inventions occur with probability 0, it is instructive to consider a related model, the *research contest* model of one-shot Bernoulli trials across the two firms with respective statistically independent success probabilities of λ for the informed firm, and μ without agreement and no disclosure, or D with agreement and disclosure, for the uninformed firm. In this alternative model, without agreement on a fee schedule and no disclosure, ties occur with probability $\mu\lambda$, and we may then simply assume Bertrand competition at the post-R&D stage, implying the loss for both firms of the invention value ($V = 1$). With agreement and disclosure, ties occur with probability λD. Firm 2 contractually pays $f_\alpha(D)$ to firm 1 whenever firm 2 invents. Furthermore, in the event of tied inventions firm 1 can precommit to *not* competing in the product market, because its knowledge licence is "exclusive", contingent on invention by firm 2.

Under these simplifying assumptions, we easily get

$$L_1^0(\mu,\lambda) = \lambda(1-\mu), \quad L_2^0(\mu,\lambda) = \mu(1-\lambda),$$
$$L_1(D,\lambda,f_\alpha(D)) = \lambda(1-D) + Df_\alpha(D), \quad L_2(D,\lambda,f_\alpha(D)) = D - Df_\alpha(D),$$

with

$$\begin{aligned} Df_\alpha(D) &= (D-\mu)[D+\alpha-\alpha D] + \alpha D\mu \\ &= (1-\alpha)D^2 + (\alpha-\mu+2\alpha\mu)D - \alpha\mu. \end{aligned}$$

Clearly

$$\frac{\partial L_1}{\partial \lambda} \text{ and } \frac{\partial^2 L_1}{\partial \lambda \partial D} = -1 < 0,$$

globally, so that the violation of the usual Spence-Mirrlees single-crossing property (Lemma 1), and the key feature of the informed agents' choices noted in Lemma 2 above, continue to obtain. In the contest model, an additional economic rationale behind this violation is present: the augmenting of D by a λ-type firm 1 increases the probability of *tied* invention λD, whence firm 1 only collects $f(D) < 1$, rather than the full value of the invention 1, and clearly $[\partial^2(\lambda D)/\partial\lambda\partial D] = 1 > 0$. More directly, note that the $Df_\alpha(D)$ functions are convex in D, and hence $[\partial^2 L_1/\partial D^2] > 0$ globally, so that arg $\max_{D\in[\mu,\lambda]} L_1(D,\lambda,f_\alpha(D))$ are always extremal.

Proof of Proposition 1. For any $\alpha \in [0,1]$ the direct bargaining mechanism defined by the sure-agreement and full disclosure of knowledge, together with the fee schedule f_α defined in equation (3.2) above, clearly ensures (EF), and (IR) under full disclosure. Hence, only the (IC) conditions (for full disclosure) have to be verified.

For that purpose, first, we may check that the function $Df_\alpha(D)$, as defined by (3.2), is globally convex in $D \in [\mu, \overline{\lambda}]$, for every $\alpha \in [0,1]$. Indeed,[17]

$$\frac{d^2(Df_\alpha(D))}{dD^2} = \frac{[(4\mu^2 + 6\mu\delta + 2\delta^2) - \alpha(4\mu\delta + 2\delta^2)]}{(D+\mu+\delta)^3} > 0, \tag{3.8}$$

since $\alpha \in [0,1]$.

Second, for $D(\lambda)$, a continuously differentiable function satisfying $(\partial/\partial D)L_1(D(\lambda), \lambda, f_\alpha(D(\lambda))) = 0$ in an open neighbourhood of some λ' given condition (3.6), we have that in this neighbourhood

$$\frac{\partial}{\partial D}L_1(D(\lambda), \lambda, f_\alpha(D(\lambda))) = \frac{(d/dD)[D(\lambda)f_\alpha(D(\lambda))]}{(\lambda + D(\lambda) + \delta)} - \frac{[\lambda + D(\lambda)f_\alpha(D(\lambda))]}{(\lambda + D(\lambda)+\delta)^2} = 0,$$

or, using (2.3),

$$\frac{d}{dD}[D(\lambda)f_\alpha(D(\lambda))] = L_1(D(\lambda), \lambda, f_\alpha(D(\lambda))).$$

Moreover, using the Envelope Theorem, we have in this neighbourhood of λ',

$$\begin{aligned}
&\frac{d^2}{dD^2}[D(\lambda)f_\alpha(D(\lambda))]\frac{dD(\lambda)}{d\lambda} \\
&= \frac{d}{d\lambda}L_1(D(\lambda), \lambda, f_\alpha(D(\lambda))) \\
&= \frac{\partial}{\partial\lambda}[L_1(D(\lambda), \lambda, f_\alpha(D(\lambda)))]_{D(\lambda)} + \left[\frac{D}{\partial D}L_1(D(\lambda), \lambda, f_\alpha(D(\lambda)))\right]_\lambda \frac{dD(\lambda)}{d\lambda} \qquad (3.9) \\
&= \frac{\partial}{\partial\lambda}[L_1(D(\lambda), \lambda, f_\alpha(D(\lambda)))]_{D(\lambda)} \\
&= \frac{D(\lambda)(1 - f_\alpha(D(\lambda))) + \delta}{(\lambda + D(\lambda) + \delta)^2} > 0,
\end{aligned}$$

since $\delta > 0$ and $f_\alpha(D(\lambda)) \in [0,1]$.

Finally, with equations (3.8) and (3.9) together implying $dD(\lambda)/d\lambda > 0$ in the neighbourhood of λ', we get by using Lemma 2 that $D(\lambda')$ is an interior minimum w.r.t. D of $L_1(D, \lambda', f_\alpha(D))$;

[17] Now assuming $A(D) = (2\alpha - 1)$; $B(D) = (1-\alpha)(4D+\delta)/(D+\mu+\delta)$; $C(D) = -2\alpha\mu/(D+\mu+\delta)$; $E(D) = \alpha(D+\mu)/(D+\mu+\delta)$; $F(D) = -(2D+\delta)/(D+\mu+\delta)$; $G(D) = -D(2D+\delta)/(D+\mu+\delta)^2$, we may simply write from (3.2): $(d(Df_\alpha(D)))/dD = [A(D) + B(D) + C(D) + E(D)F(D) + G(D)]$, and then derive.

for any $\lambda' \in [\underline{\lambda}, \overline{\lambda}]$, $L_1(D, \lambda', f_\alpha(D))$ *cannot* have a local maximum w.r.t. D at any $\mu < D < \lambda'$. Thus, with individual rationality holding by construction, full disclosure $D^*(\lambda)$ is a global maximizer w.r.t. D of $L_1(D, \lambda, f_\alpha(D))$ in the domain $D \in [\mu, \lambda]$, for all $\lambda \in [\underline{\lambda}, \overline{\lambda}]$, and $\alpha \in [0, 1]$, uniquely so for $\alpha > 0$. ■

To summarize, because of the reverse Spence-Mirrlees single-crossing property (Lemma 1), no fee schedule, even chosen outside the class $\{f_\alpha\}$, can make a set of increasing-in-λ partial-disclosure D choices local interior maxima for firm 1 (Lemma 2). Moreover, for any chosen fee schedule in the class $\{f_\alpha\}$, the expected payoff of firm 1 has no local interior maximum in$D$ for any λ, thus leading to a corner solution: either $D = \mu$ or $D(\lambda) = \lambda$ is chosen by the informed agent 1 of type λ. Finally, since any fee schedule f_α implies that under full disclosure all type-dependent participation (IR) constraints are satisfied; both firms receive at least their outside option payoffs. Thus, we obtain full disclosures of their interim innovative knowledges by licensors using direct mechanisms, as global maxima that are strict for all $\alpha > 0$.

For further assessment of the robustness of these results, reference to a different set of assumptions might be useful. The discussion so far in this section has been conducted assuming *invention-contingent fee schedules*. An alternative knowledge licensing fee structure assumes knowledge licensing fees which are *uncontingent* on invention by the licensee. An *uncontingent fee schedule* is a function $f : [\mu, \overline{\lambda}] \to [0, 1]$ where $f(D)$ is the amount paid by the licensee (the uninformed firm 2) to the licensor (the informed firm 1). We have, as above $f(D) \geq 0 = f(\mu)$. In the Poisson race, instead of (2.3), the payoffs of a type λ licensor when disclosing $D \leq \lambda$ are

$$L_1(D, \lambda, f(D)) = \frac{\lambda}{\lambda + D + \delta} + f(D).$$

Thus at an interior critical point with respect to D of $L_1(D, \lambda, f(D))$, we have

$$\frac{\partial^2 L_1}{\partial \lambda \partial D} = \frac{\lambda - (D + \delta)}{(\lambda + D + \delta)^3},$$

which is negative if and only if $\lambda < D + \delta$. Hence the analysis of Proposition 1 would still apply qualitatively in this case, whenever $\overline{\lambda}(\mu + \delta)$. The contrary case corresponds to a situation where the usual Spence-Mirrlees single-crossing condition does hold true over part of the domain of feasible disclosure D, for at least a subset of types in $[\underline{\lambda}, \overline{\lambda}]$, thus creating the possibility of licensing equilibria with *partial* (interior maximal) disclosure of knowledge.

A second interesting comparison is with the model of Bhattacharya and Ritter (1983), who also consider knowledge disclosure in the context of a Poisson race, but where the payoff of the informed firm of type λ given its disclosure $D \leq \lambda$ is, instead of (2.3)

$$L_1(D, \lambda, W(D)) = \frac{\lambda}{\lambda + D + \delta}\left(1 - \frac{I}{W(D)}\right),$$

where I stands for a lump-sum investment required of both informed and uninformed firms to participate further in the R&D race, and $W(D)$ is the *financial* (equity) market *value* of the knowledgeabe firm under disclosure D, which serves as a costly *signal* of its λ-type[18] that is observable (by R&D rivals and investors), but not verifiable. This new investment I has to be financed externally, and disclosure D affects the terms on which the informed firm can finance I by affecting $W(D)$; the informed firm's shareholders sell new equity to the fraction $I/W(D)$ of the firm when disclosing D. The Spence-Mirrlees single-crossing property , which was precluded under (2.3), now obtains. This is because

$$\frac{\partial}{\partial \lambda}\left[-\frac{\partial L_1/\partial D}{\partial L_1/\partial W}\right] = \frac{\partial}{\partial \lambda}\left(\frac{W^2(D)(1 - I/W(D)}{I(\lambda + D + \delta}\right) < 0.$$

This key change deals to a Pareto-supremer separating signalling equilibrium $D(\lambda)$, with $D(\underline{\lambda}) = \mu, D(\lambda) < \lambda$ strictly increasing in λ and maximizing $L_1(D, \lambda, W(D))$ w.r.t. D, and also, $\forall\, \lambda \in [\underline{\lambda}, \overline{\lambda}]$

$$W(D(\lambda)) = \frac{\lambda}{\lambda + D(\lambda) + \delta},$$

a condition for a separating signalling equilibrium with competitive financial markets.

[18]This is a modification of Bhattacharya and Ritter (1983) where the number of competitors is endogenous, determined by free entry and the disclosure choice $(D(\lambda))$ of the informed firm, and the resulting inference about its type λ by the uninformed firms in a Perfect Bayesian equilibrium. Bhattacharya and Ritter (1983) assume that licensing of interim research knowledge disclosed (to the financial market and also, as a result, to competitors) is *not feasible*, as courts could *never* verify the amount or quality of knowledge disclosed. See also Bhattacharya and Chiesa (1995) for a related model, in which intermediated financing may preserve the privacy of disclosed knowledge.

3.2 Sequential bargaining with incomplete information: One-sided offers games

We now proceed to consider implementation by infinite-horizon sequential bargaining games of (repeated) offers by one (buyer or seller) party coupled with accept/reject decisions by the other party. As in Samuelson (1984), Cramton (1984) and Ausubel and Deneckere (1989a,b), we shall consider pure-strategy sequential equilibria of these games. It is known that, to any such equilibrium, leading to agreement in period $n(\lambda)$ with disclosure $D(\lambda)$ and a fee $f(D(\lambda))$ for an informed firm of type $\lambda \in [\underline{\lambda}, \overline{\lambda}]$, one can associate an incentive compatible and individually rational direct static bargaining mechanism (P, f) which is payoff equivalent and where the probability of agreement is given by $P(\lambda) = \exp(-\delta \Delta n(\lambda))$, where Δ is the time interval between successive offers. This is the Revelation Principle applied to our context. Our goal now is to explore the reverse direction and identify two of the direct bargaining mechanisms $(P \equiv 1, f_\alpha)$, shown in Proposition 1 to satisfy (EF), (IC) and (IR), that are *implementable* in the sense of being payoff-equivalent to a (unique) sequential equilibrium of an infinite-horizon one-sided-offer bargaining game. We consider the equilibrium set of these games for Δ sufficiently close to 0. Clearly, implementability by such a game implies equilibrium agreement in it at times $n(\lambda) = 0$, with full-disclosures and (contractual) equilibrium licence fees of $f_\alpha(D(\lambda) = \lambda)$, for every informed firm of each type λ. We shall establish the implementability of the two extreme direct bargaining mechanisms ($\alpha = 0$ and $\alpha = 1$).

The first bargaining game we consider is the following buyer-offers game. At times $t = 0, \Delta, \cdots, n\Delta$ firm 2 selects as its offer a licence fee schedule $f_t(D)$, $f_t : [\mu, \overline{\lambda}] \to [0, 1]$, and then at these times firm 1 (the informed agent) of type λ either accepts and chooses $D(\lambda) \in [\mu, \overline{\lambda}]$, or rejects. In the event of "acceptance" by firm 1 at time t, both parties agree on (sign a contract for) a licensee fee $f_t(D(\lambda))$ to be paid by firm 2 to firm 1 conditional on future invention by firm 2, and the knowledge level $D(\lambda)$ to be disclosed by firm 1. The level of knowledge actually disclosed cannot be denied or exaggerated, at least contingent on invention by firm 2; hence, the agreement must be feasible, $D(\lambda) \leq \lambda$. The following proposition shows how the uninformed-offers game can implement the direct efficient bargaining mechanism whereby all the incremental surplus from knowledge-sharing accrues to the uninformed agent.

Proposition 2 *The efficient direct bargaining mechanism resulting from the licence fee schedule f_0 is implementable as a (stationary) sequential equilibrium of the uninformed-offer game. This equilibrium consists in having the uninformed agent (firm 2) offering $f_0(D)$, as defined by equation (3.3) above, at all times $t = 0, \Delta, \cdots, n\Delta$, with, for all $\lambda \in [\underline{\lambda}, \overline{\lambda}]$, the λ-payoff $L_1(\lambda, \lambda, f_0(\lambda)) = L_1^0(\mu, \lambda)$. Moreover, all sequential equilibria are outcome equivalent.*[19]

Proof: To show that the sequential equilibrium described above exists, with each λ-type firm 1 accepting at $t = 0$ and choosing $D(\lambda) = \lambda$, and with firm 2 always offering f_0, we note the following. First, if faced with a *stationary* sequence of $\{f_0(D)\}$ offers at all times $t = 0, \Delta, \cdots, n\Delta$, it is optimal for any λ-type firm to prefer acceptance at $t = 0$ and, by the IC property proved in Proposition 1, to prefer $D(\lambda) = \lambda$. Second, note that, given *any other* history of offers by firm 2, and associated strategies of firm 1 leading to rejection of offers until time $(n-1)\Lambda$, and given *any revised beliefs* of firm 2 $\Pi_n(\lambda)$ about firm 1, it is still optimal for it to start offering $f_0(D)$ at all times $n\Delta$, $(n+1)\Delta$ *etc.*, with acceptance by firm 1 at $n\Delta$ with $D(\lambda) = \lambda$. Hence, by backward induction, firm 2 should offer $f_0(D)$ at $t = 0, \Delta, \cdots, (n-1)\Delta$.

These arguments[20] clearly establish the existence of the proposed equilibrium. Because of discounting, firm 1 would lose by postponing acceptance. Firm 2 would lose from partial disclosure. Thus, any other sequential equilibrium would also imply immediate acceptance, and offers by firm 2 equal to $f_0(D)$ for $D \in [\underline{\lambda}, \overline{\lambda}]$. ■

[19] In the ongoing-R&D case, the existence proposition holds. More equilibria are possible, since in that case firm 1 has nothing to lose by postponing acceptance of the $f_0(D)$ offer, and continuing its own R&D. These other equilibria, which are payoff-equivalent for each λ-type agent 1 compared to the $\{f_0(D), D(\lambda) = \lambda\}$ equilibrium we consider, disappear when the offers by firm 2 are restricted so as to preserve a minimal percentage of the surplus for firm 1: $\{f : [\mu, \overline{\lambda}] \to [0, 1] | f_\varepsilon(D), \forall D \in [\mu, \overline{\lambda}]\}$, for any arbitrarily small fixed $\varepsilon > 0$ and $f_\varepsilon(D)$ is in the class defined by (3.2). Then, in the unique equilibrium, firm 2 offers $f_\varepsilon(D)$ at all times (instead of $f_0(D)$), and firm 1 of type λ strictly prefers to accept at $t = 0$ with $D(\lambda) = \lambda$.

[20] In the ongoing-R&D case, *non*-invention by agent 1 up to some time $n\Delta$ is informative about its type λ. We have no need to calculate these beliefs or conjectures, since the optimal continuation strategies of the uninformed agent are stationary, and independent of these beliefs about λ in our model.

Proposition 2 is to be contrasted with the recent developments in the literature on bargaining under incomplete information over a private good, mentioned in the introduction. These models have concentrated on the so-called Coase property. For a typical model, take the problem of bargaining over the trade of one unit of a good between a seller having a known opportunity cost normalized at zero, and a buyer whose valuation of the good is private information; the model is of independent "private values". The seller, the uninformed party, makes offers of purchase prices at discrete dates over time. The buyer, the informed party, says yes or no. The Coase (1972) conjecture states that the probability that an informed buyer with strictly positive gain from trade will accept an offer, within any fixed interval of time, goes to ones as the length of the period between the uninformed seller's sequential offers shrinks to zero. Moreover, the equilibrium price(s) go to the greater of zero and the minimum possible valuation of the buyer.

Coase conjectured this result in the related context of monopoly pricing of a durable good where the buyer's *ex ante* probability distribution of valuations is interpreted as a cross-sectional distribution of consumers with varying willingness to pay for the good. Its general validity has been established by Gül, Sonnenschein and Wilson (1986), using equilibria in which the informed buyers' strategies have (in addition to more technical assumptions) a Markov property: when a price is offered that is lower than all preceding prices, the buyer's decision is independent of the earlier price history. In contrast, our Proposition 2 is an "anti-Coase result": the (unique) equilibrium outcome of our sequential bargaining game, with all offering power in the hands of the uninformed agent, is to have corner surplus sharing, with *zero* surplus for *each* type of the informed agent. Hence, in our *excludable public good environment*, our non-linear pricing (uninformed) monopsonist does as well as a perfectly discriminating (informed) knowledge buyer, with or without commitment to its offer schedule.[21]

Consider now a specification of the *seller offer game*. At times $n\Delta, n = 0, 1, \cdots$, an offer by the informed firm 1 of type λ is taken, for reasons spelt out below, to be a 2-vector $\langle D, f(D)\rangle \in [\mu, \lambda] \times [0, 1]$, which is accepted or rejected by the uninformed firm 2 at times $n\Delta$. We have the

[21] Ausubel and Deneckere (1989a,b) show that, in the "no gap" case where no gains from trade is a possibility ($\underline{\lambda} = \mu$ in our model), there are other non-Markov sequential equilibria than those satisfying the Coase conjecture.

following simple result, showing that all the surplus from knowledge disclosure (relative to the outside options) accrues to the licenser.

Proposition 3 *The direct bargaining mechanism* $\{P(\lambda) = 1, D(\lambda) = \lambda, \forall\, \lambda; f_1(D)\}$ *is implementable as a (stationary) sequential equilibrium of the uninformed offer game. It consists in having the informed agent, firm 1 of type* $\lambda \in [\underline{\lambda}, \overline{\lambda}]$*, offering the pair* $\langle D(\lambda) = \lambda, f_1(\lambda)\rangle$ *at all times* $t = 0, \Delta, \cdots, n\Delta$*, and firm 2 accepting at time* $t = 0$*. This equilibrium is unique.*[22]

Proof: That it is a stationary equilibrium for all licensors of types $\lambda \in [\underline{\lambda}, \overline{\lambda}]$ to offer at all times the same pair $\langle D, f_1(D)\rangle$ with $D = \lambda$, thus capturing the maximized total incremental surplus from disclosure, and for firm 2 to accept at time $t = 0$, is clear enough. To accept immediately is also strictly preferred by firm 2, in order to avoid delaying its benefit from R&D. That this equilibrium is unique follows from applying the argument in Theorem in Ausubel-Deneckere (1989a). ■

Proposition 3 illustrates the importance of "control" by the informed firm, in order for it to extract all incremental surplus from knowledge disclosure to the buyer, even when it has all the offering power. The buyer is not even given (optimally) any choice regarding how much knowledge it wants to buy; the alternative consisting in the offering of the full $f_1(D)$ schedule, modulo $D \leq \lambda$, by each λ-type firm would *not*[23] lead to the buyer accepting immediately and choosing $D = \lambda$.

[22] In the ongoing-R&D case, a unique sequential equilibrium is obtained if the strategies of every λ-type firm are restricted to the set $\{\langle D, f(D)\rangle \in [\mu, \lambda] \times [0, 1] | f(D) \geq f_{1-\varepsilon}(D), \forall\, D \in [\mu, \lambda]\}$, for some arbitrarily small fixed $\varepsilon > 0$. Then, a λ-type firm 1 offers $\langle \lambda, {}_{1-\varepsilon}(\lambda)\rangle$ at all times, and the associated implementable direct bargaining mechanism is $\{P(\lambda) = 1, D(\lambda) = \lambda, \forall\, \lambda; f_{1-\varepsilon}(D)\}$. With respect to pre-R&D bargaining game, the stationary strategy of a λ-type firm 1 is here simply replaced by $\langle \lambda, f_{1-\varepsilon}(\lambda)\rangle$. Accepting immediately is strictly preferred by firm 2, in order to avoid a delay in getting its (small) share of the incremental surplus from knowledge disclosure.

[23] The offers of $\{f_1(D) \mid D \leq \lambda\}$ by each seller, and acceptance at $t = 0$ with choice $D = \lambda$ by the buyer, is *not* a sequential equilibrium. Since $[L_2(D, \lambda, f_1(D)) - L_2^0(\mu, \lambda)] = [(D(1 - f_1(D)))/(D + \lambda + \delta) - \mu/(\mu + \lambda + \delta)]$, it is easy to see that (by design) this difference equals 0 at $D = \lambda$, but it is strictly positive for some $D < \lambda$. Hence, given such a licensing offer schedule, the buyer would strictly prefer to choose partial disclosure of the knowledge of firm 1, and a lower licence fee.

4 Conclusion

In this paper, we have analyzed a problem of bargaining between an informed seller and an uninformed buyer of knowledge, over the disclosure of the knowledge of the former and the associated licence fee. The nature of the knowledge is that of transferable interim research findings, metrized as the resulting Poisson intensities of invention in an R&D race over time. Throughout our analysis, we have emphasized the *public good feature* of such interim research knowledge, which can in principle be utilized for the invention prospects of *both* the parties in the R&D race.

Our results are quite striking. We have shown that there is a very large class (in surplus shares) of mechanisms which are incentive compatible, individually rational, and efficient, implying no delay in agreement and full knowledge disclosure. Moreover, for sequential equilibria of uninformed offers bargaining games, a key component of the Coase conjecture fails. When having all the bargaining (or offering) power, the uninformed knowledge buyer may obtain, in a (unique) sequential equilibrium, full disclosure of the seller's knowledge while surrendering *none* (arbitrarily small proportion) of the incremental researchers' surplus that is created by the disclosure of such knowledge.[24]

A couple of factors could *potentially* modify our sharp results, and we consider these in turn. The first is that of endogenous and interior choice of costly development efforts with and without knowledge sharing between the buyer and the seller. The seller's (post-knowledge acquisition *cum* disclosure) effort choice would typically be higher without knowledge sharing, as shown by Bhattacharya, Glazer and Sappington (1992). However, this feature is likely to simply serve to redefine the outside option of the seller, and our result, that in the uninformed offer

[24] A similar extremal surplus sharing result is in fact also true for an alternating offers bargaining game with *incomplete information a priori* about the *level*, but not about the technical *content* of the knowledge of firm 1 in the Poisson race. In such a game, as the time between offers $\Delta \to 0$, the equilibrium payoff of the informed agent would converge (with full disclosure) again to its outside option $L_1^0(\lambda, \mu)$, since $\frac{1}{2}[L_1(\lambda, \lambda, f(\lambda)) + L_2(\lambda, \lambda, f(\lambda))] = \lambda/(2\lambda + \delta) < L_1^0(\lambda, \mu) = \lambda/(\lambda + \mu + \delta)$. This observation follows from the results of Binmore, Rubinstein and Wolinsky (1986).

bargaining equilibrium all the sellers obtain no more than their outside options, is likely to still obtain. Second, the simultaneous presence of *multiple* and competing knowledge *buyers* could also potentially modify our extremal surplus-sharing results. However, if knowledge disclosure is only verifiable in courts contingent on (first) invention by a *licensee*, it may be difficult for the licensor to credibly commit to exclusive licensing to a proper subset of buyers. This issue deserves serious further research, and would involve difficult extensions of the methodology initiated by Jehiel and Moldovanu (1995), among others, on multilateral bargaining with externalities across agents from trades by other agents.

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