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DISCUSSION PAPER

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Abstract

In this paper we review some of the literature on R&D collective arrangements using game theoretical concepts and considering various settings, involving either complete or incomplete contracts. Patent protection, licensing in various industry contexts as well as the role of various factors such as product differentiation, innovation magnitude and asymmetric information are considered. The relation of innovative activity to the intensity of competition is reconsidered and the benefit of various types of cooperative R&D-agreements in presence of externalities are reviewed. The last two sections are devoted to contracting issues.

Keywords: cost-reducing innovations, cooperative R&D-agreements, development efforts, incomplete contracting.

JEL Classification: D21, D43, D45, L13, O32

[1] Sadly Sudipto Bhattacharya passed away while this chapter was being completed. As a friend and co-author, he has been a constant source of inspiration.
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There are several aspects of innovative activity that makes it more complex to analyze than the production and distribution of standard physical goods. Innovative activity uses and produces knowledge. This is both costly and risky and the resulting product has (at least partially) the main characteristics of a public good: it is non-rival and non-excludable. Without any sort of protection, individual agent would have little incentive to do research by fear of unsuccessful research effort or by fear of imitation by others (through spillovers or free access).

Outside the possibility of secret holding or lead time and reputation, protection typically relies on some kind of collective arrangements, involving more or less legal intervention, according to degree of verifiability by a court and the willingness of the public authority. Patent protection and the possibility of licensing the innovation is one example. Cooperative R&D or Research Joint-Ventures is another. Patent protection increases the appropriability of the innovation and allows the selling of the innovation to others. Cooperative R&D or Research Joint-Ventures internalize knowledge spillovers, that is the flowing of knowledge from one agent to another. But cooperation may take many contractual forms and does involve moral hazard and adverse selection issues.

In this chapter we will review R&D collective arrangements using game theoretical concepts and considering various settings, involving either complete or incomplete contracts. Section 1 is devoted to patent protection and the comparison of the main forms of licensing in various industry contexts, structures or sizes, and to the role of various factors such as product differentiation, innovation magnitude and asymmetric information. In Section 2, the long debated issue of the relation of innovative activity to the intensity of competition is reconsidered and the benefit of various types of cooperative R&D-agreements in presence of externalities are reviewed. The last two sections are devoted to contracting issues. Section 3 reviews the design of licensing mechanisms allowing for full knowledge sharing under incomplete information and optimal development efforts before the production stage. This is done in a complete contract setting. Incomplete contracts are considered in Section 4 in order to deal with cumulative or sequential innovation and the associated moral hazard problems combining research and development efforts, and the possibility of several buyers for the innovation.

1. Patenting and licensing

A patent grants an innovator monopoly rights over the use of an innovation for a given period of time. It seeks to provide incentive to innovate as well as to disseminate the innovation.

Licensing is a standard way through which an innovation can be diffused. Licensing policies in practice take various forms, but they can be classified into three broad categories: licensing by means of upfront fees, royalties, and policies that combine both fees and royalties.

The theoretical literature of patent licensing can be traced back to Arrow (1962) who argued that a perfectly competitive industry provides a higher incentive to innovate than a monopoly. Licensing under oligopoly was first studied by Kamien and Tauman (1984, 1986) and Katz and Shapiro (1985, 1986).[1] The licensing problem in an oligopoly model involves aspects of strategic interaction which necessitates the use of a game theoretic analysis. The strategic interaction is particularly interesting when the innovator is an incumbent firm in an industry since in such a case it has to take into consideration the effect of licensing to its rival firms on its future profits in the oligopoly market. The analysis of licensing problems under asymmetric information (e.g., when some aspect of the innovation is not perfectly known to a potential licensee, or when certain characteristics of the potential licensees are not perfectly known to the innovator) naturally uses tools of principal-agent models. Thus, patent licensing is an area of economics that involves applications of several strands of game theory.

The literature has mostly focused on licensing of cost-reducing innovations, i.e., innovations that result in lower production costs for competing firms who are potential licensees.[2] Considering innovators that are outsiders to the industry, the early literature concluded that licensing by means of upfront fees or auction[3] dominates royalty licensing for an outside innovator in an oligopoly (Kamien and Tauman, 1984, 1986; Kamien, Oren and Tauman, 1992). However, empirical studies point out the frequent use of royalties in practice (Firestone, 1971; Taylor and Silberston, 1973; Caves, Crookell and Killing, 1983; Rostoker, 1984). It has been subsequently argued that royalty licensing could be optimal when the innovator is one

[1] the early literature, see also Gallini (1984), Gallini and Winter (1985), Katz and Shapiro (1987), Muto (1987) and Rockett (1990a). See Kamien (1992) for an excellent review of the early literature. Some recent For papers include Choi (2001), Filippini (2002), Erkal (2005a), Liao and Sen (2005), Erutku and Richelle (2006), Giebe and Wolfstetter (2008) and Martin and Saracho (2010).

[2] See Stamatopoulos and Tauman (2008) for the analysis of licensing of innovations that lead to better product quality for firms.

[3] It is optimal for the innovator to choose an upfront fee to extract the maximum possible surplus from the licensees. The best way to do this is through an auction policy. As shown in Katz and Shapiro (1985) and Kamien and Tauman (1986), compared to a flat upfront fee, an auction generates more competition that increases the willingness to pay for a license.

of the incumbent firms in an oligopoly. Royalties are appealing for an incumbent innovator, because they provide the innovator with a competitive edge by raising the effective cost of its rivals. This reasoning was put forward by Shapiro (1985), later formalized by Wang (1998) in a Cournot duopoly and extended to a Cournot oligopoly by Kamien and Tauman (2002).[4] The literature has also sought to explain royalties on the basis of diverse factors such as variation in the quality of the innovation (Rockett, 1990), risk aversion (Bousquet, Cremer, Ivaldi and Wolkowicz, 1998), product differentiation (Muto, 1993; Wang and Yang, 1999; Poddar and Sinha, 2004; Erkal, 2005b), or integer constraint of number of licenses (Sen, 2005a).

One strand of the literature has considered the role of informational asymmetry to explain the use of royalty licensing. Gallini and Wright (1990) have studied a model of licensing where the value of the innovation is private information to the innovator, who signals the value through the contract offer. They have shown that an upfront fee licensing contract is offered for innovations with a low value, while for high-value innovations, the innovator offers a royalty contract. In a model of asymmetric information where an innovator interacts with a monopolist who is privately informed of the value of the innovation, Macho-Stadler and Perez-Castrillo (1991) have shown that the optimal menu of contracts proposed by the innovator is separating. The contract for the good quality innovation involves only upfront fees, while for the bad quality innovation, the contract is a combination of fixed fee and royalty. Beggs (1992) has considered the situation where the innovator is the uninformed party, while the buyer knows the true value of the innovation. In this setting it is shown that royalty licensing can make a separating equilibrium possible,

[4] See also Marjit (1990) and Wang (2002) for other issues pertaining to incumbent innovators.

and doing so, may ensure that trade takes place in cases where it fails under licensing via upfront fees. Sen (2005b) has studied the problem of licensing of a cost-reducing innovation between an innovator and monopolist firm, where the cost of the monopolist is its private information. It is shown that when the innovator uses combinations of fees and royalties, the low-cost monopolist is always offered a pure fee contract, while for the contract offered to the high-cost monopolist, the royalty rate is always positive, and moreover, there are cases where this is a pure royalty contract. To sum up, the underlying common theme is, in one form or another, that an output-based royalty is used as an effective separating device under asymmetry of information.

Considering general licensing policies in combinations of upfront fees and royalties for both outside and incumbent innovators, Sen and Tauman (2007) have shown that consumers and the innovator are better off, firms are worse off and the social welfare is improved from licensing. Furthermore the optimal policies depend on the industry size as well as the magnitude of the innovation; in particular, when the industry size is not too small, licensing of relatively significant non-drastic innovations[5] involves a positive royalty. They have also shown that compared to an incumbent firm, an outside innovator invests more in R&D and has higher incentives to innovate. Combinations of fees and royalties have been also studied in other specific duopoly models. In a differentiated duopoly where the innovator is one of the incumbent firms, Fauli-Oller and Sandonis (2002) have shown that the optimal

[5] A cost-reducing innovation is *drastic* (Arrow, 1962) if it significant enough to create a monopoly with the reduced cost; otherwise it is *non-drastic*. An incumbent innovator of a drastic innovation has no incentive to license its innovation, since it can earn the entire monopoly profit with the reduced cost by using the innovation exclusively. In any industry of size two or more, an outside innovator of a drastic innovation can also earn the monopoly profit by selling the license to only one firm through an auction. See Sen and Stamatopoulos (2009a) for the complete characterization of optimal licensing policies for an outside innovator of a drastic innovation.

licensing policy always includes a positive royalty. Under a Stackelberg duopoly where the innovator is the Stackelberg leader, Filippini (2005) has shown that the optimal policy has only royalty and no upfront fee.

Regarding the relation between industry structure and incentives to innovate, Arrow's initial analysis has been further qualified. It has been shown that, under royalty licensing, the perfectly competitive industry provides the highest incentives to innovate (Kamien and Tauman, 1986). However, when the innovator uses combinations of fees and royalties, the highest incentives are provided by industries where the number of firms is not too large or too small (Sen and Tauman, 2007) although Arrow's basic intuition is still robust in that a perfectly competitive industry always provides a higher incentive than a monopoly. We will come back to such non-monotonicity results in the next section.

In a recent paper Sen and Tauman (2012) have considered combinations of upfront fees and royalties for both outside and incumbent innovators in a Cournot oligopoly under a class of general demand functions where the elasticity is non-decreasing in price. Kamien, Oren and Tauman (1992) also studied the same general demand framework, but their analysis was restricted to only outside innovators with pure upfront fee and pure royalty policies. Sen and Tauman (2007) considered general policies in combinations of fees and royalties, but they restricted to linear demand. Sen and Tauman (2012) have extended both of these earlier papers to present a unified approach. They show that many results obtained under linear demand continue to hold in this general set-up. Specifically it is shown that (i) for generic values of magnitudes of the innovation, a royalty policy is better than fee or auction for relatively large sizes of the industry, (ii) under combinations of fees and royalties, provided the innovation is relatively significant, (a) there is always an optimal policy where the innovation is licensed to practically all firms of the industry and (b) any optimal policy includes a positive royalty.

Another interesting recent development in the literature is to consider the licensing problem in a cooperative game theoretic framework instead of the standard non cooperative approach. There is a small but growing literature on the cooperative approach (Tauman and Watanabe, 2007; Watanabe and Muto, 2008; Jelnov and Tauman, 2009; Kishimoto, Watanabe and Muto, 2011). One key result of this literature is that as the number of firms in an oligopoly increases asymptotically, the solutions of non-cooperative and cooperative approaches give the same value for the patent.

Other issues addressed in the literature include leadership structure (Kabiraj, 2004; 2005), strategic delegation (Mukherjee, 2001; Saracho, 2002), scale economies (Sen and Stamatopoulos, 2009b) and the strategic aspects of selling patent rights (Tauman and Weng, 2012).

Driven by the greater availability of firm-level data, empirical research on licensing has also grown in recent years (e.g., Macho-Stadler, Martinez-Giralt and Perez-Castrillo, 1996; Anand and Khanna 2000; Yanagawa and Wada 2000). Furthermore, studies have been carried out on licensing contracts from industry data in specific countries such as Germany (Czarnitzki and Kraft, 2004), Japan (Nagaoka, 2005), Spain (Mendi, 2005) and India (Vishwasrao, 2007). One key insight of this empirical literature is that licensing contracts often vary with respect to country-specific institutional characteristics.

2. *Varying competition toughness, Spillovers and Research Joint-Ventures*

When assessing the positive influence of cooperation on innovative activity, the first argument that should be recalled, following the traditional Schumpeterian view, is the negative association between the number of firms in an industry and its investment level in R&D. But, as well stressed by Dasgupta and Stiglitz (1980), the causality is difficult to establish. On the one hand, innovation gives the innovating firm a monopoly advantage, at least partially and temporarily. On the other hand some monopoly rent is required to allow for R&D expenditures. Also important is the Arrowian notion of "incentive to invent" which is determined by the difference between the current and the post-invention profit flows. Arrow (1962) argument that the incentive to invent is larger in a competitive industry than in monopoly can again be qualified. It does not take into account the possibility for firms to compete strategically both in the market and in R&D. This is the crucial element analyzed by Dasgupta and Stiglitz (1980) in a symmetric and deterministic model of oligopolistic competition with strategically chosen cost-reducing R&D expenditures and free entry. With the number of firms determined by a zero-profit condition based on the R&D investment cost per firm, a larger equilibrium level of R&D expenditures is associated to a smaller equilibrium number of firms. Since both concentration and R&D levels are endogenously determined, no causality can be deduced[6]. An important consequence of R&D competition clearly appears. Although each firm may choose a small R&D level with respect to the social optimum, through wasteful duplication

[6] Dasgupta and Stiglitz (1980) mention though that innovation may become negatively correlated to concentration when concentration is high.

aggregate R&D expenditures become excessive.

The same kind of excess also appears in stochastic models of patent race (Loury, 1979, Lee and Wilde, 1980) where firms independently compete for a cost reducing innovation over time. The time of innovation is a random variable assumed to follow an exponential distribution with hazard rate increasing with R&D expenditure. The stochastic process is Poisson and each firm chooses its R&D expenditure non-cooperatively. Competition on the product market is of the Bertrand type and patent protection is assumed to be perfect and infinitely lived so that the first inventor gets all the benefit. Since at equilibrium all firms invest in R&D there is excessive aggregate investment. However the expected time of innovation is shorter when the number of firms is larger.

The number of competing firm, though, is only one element determining the intensity of competition. In a deterministic growth model with two sectors - a non-innovative perfectly competitive sector and an oligopolistic sector with differentiated products - van de Klundert and Smulders (1997) compare the effect of different regimes of oligopolistic competition, namely Bertrand vs Cournot, on innovation and growth. The number of firms is still determined under free entry by the zero profit condition. Under the more competitive Bertrand regime the innovation rate and growth is higher than under the Cournot regime. But this is somewhat paradoxical since it is essentially due to the reduction of the equilibrium number of firms (and hence a reduction in product variety) under Bertrand competition, each firm having a larger size allowing for more R&D expenditures. This effect is reinforced by an increase in size of the oligopolistic sector due to lower relative prices. In this way, toughness of competition is good for innovation and growth (although it remains insufficient from a welfare point of view).

Another view of the relationship between competition and innovation is defended in the work of Aghion et al. (2005) which gives both empirical evidence and a theoretical argument in favour of an inverted-U relationship. They also analyse a general equilibrium multisectoral growth model with, in each sector, a patent race between two firms trying to move one technological step ahead by investing noncooperatively in a Poisson hazard rate. Thanks to imitation (or spillovers) the lagging firm is supposed to remain in business and never to be more than one step behind. At the Markov-stationary equilibrium the set of sectors is partitioned into two types of industries, those where the duopolists are at the same technological level (neck-and-neck) and those where there is a technological gap (one firm leading, the other lagging). In each sector the intensity of competition is modelled through the inverse of the degree of collusion in the product market that takes place when the two firms are neck-and-neck. The inverted-U relationship between the intensity of innovation and the (average) intensity of competition at equilibrium is fully explained by the difference in incentives to innovate in a leveled or unleveled sector. When competition is weak, the lagging firm in an unleveled sector has strong incentives to catch up so that the unleveled state does not last and the industry spends most of the time in the leveled state where R&D intensity is always increasing with the toughness of market competition (in order to "escape" competition). But when competition becomes tougher the R&D-intensity chosen by a lagging firm in an unleveled sector decreases, as the reward to innovation diminishes, and a Schumpeterian effect appears (and becomes dominant under sufficiently tough competition) in the industry. By averaging R&D-intensities across sectors one gets the inverted-U pattern.

Also in a multisectoral model, with overlapping generations of consumers and firms and allowing for an endogenously determined number of firms, d'Aspremont, Dos Santos Ferreira and Gérard-Varet (2010) obtains a similar non-monotonicity result but sector by sector. A concept of oligopolistic equilibrium, with parameterized intensity of market competition varying continuously between Cournot and Bertrand, is used to measure competitive toughness. In their first period of life all firms are symmetric and choose noncooperatively their investment in R&D which determine their probability of success. In the resulting Bernoullian random process several firms might be simultaneously successful and, due to spillovers, unsuccessful firms may remain active if the cost advantage is not too large and market competition not too tough. Then the incentive to invent, as measured by the incremental gain of innovating, is increasing with competitive toughness since the gap between the markets shares of successful and unsuccessful firms increases, implying a higher concentration index (e.g. Herfindahl index). When competition becomes too tough (relative to the cost advantage of innovating) then unsuccessful firms are eliminated and only the successful firms compete on the market. The concentration effect disappears[7] and the incentive to invest decreases with competitive toughness, restoring the usual Schumpeterian effect.

Whether the relationship between innovation and market competition is

[7] Here the concentration effect is due to the gap between markets shares of successful and unsuccessful firms not to the reduction of the number of firms as in van de Klundert and Smulders (1997).

monotone or not, in all these models, stochastic or deterministic, the choice of R&D intensity is noncooperative and usually suboptimal from a collective point of view. This has raised the question whether allowing cooperative agreements on R&D (but not on the product market) would be beneficial by reducing wasteful duplication of research efforts and sooner or larger sharing of inventions. Both in the US, with the National Cooperative Research Act of 1984, and in the EU regulation, enabling R&D Block Exemption since 1971, the possibility of inter-firm agreements limited to R&D (under some conditions) opened the way to R&D cooperation and joint ventures that were not seen as violating anti-trust law. A large literature both empirical and theoretical followed this policy change[8].

Among the first to investigate the welfare effects of introducing R&D cooperation is Katz (1986), who analyses four-stage games differing by the intensity of competition between firms at the last (productive) stage. Before producing, each firm chooses a level of cost reducing R&D effort, the effective cost reduction for each firm depending on the others' R&D efforts according to some spillover rate. Cooperation results from symmetry and from the introduction of two preliminary stages, the first one where the firms have to choose between becoming a member of the Research Joint-venture or to remain independent[9], the second where they decide on an output-sharing rule and a cost-sharing rule (choosing to flow knowledge above the "natural" spillover rate).

[8] See Martin (2002)
[9] Katz (1986) analysis is based on the notion of "stable cartel" as defined by d'Aspremont et al. (1983). Membership decisions is a Nash equilibrium.

An important conclusion is that "cooperative R&D is most likely to have beneficial incentive effects in markets that have strong spillovers" (Katz, 1986, p.542). This statement is made more precise in a simple example by d'Aspremont and Jacquemin (1988, 1990) using a Cournot duopoly, with each firm having its own laboratory, and comparing the non-cooperative scenario at the R&D development stage to the cooperative-R&D one, where R&D efforts are chosen to maximize total profit. Under strong spillovers total welfare is higher with cooperative-R&D. This is confirmed in Kamien, Muller and Zang (1992) oligopoly model with linear demand, but allowing for more than 2 firms and varying product substitutability γ, $0 \leq \gamma \leq 1$, ($\gamma=1$ corresponding to perfect substitutability and the homogeneous good Cournot case). In their model, whatever the number of firms, the cooperative scenario yields more total welfare than the noncooperative scenario if and only if the spillover rate β is not smaller than $\gamma/2$ (this lower bound decreasing with product differentiation). Hence a similar conclusion holds in the two models for Cournot competition - cooperative R&D dominates non-cooperative R&D - although they do not introduce spillovers at the same level. Spillovers are defined in development efforts in the AJ model (output spillovers measured in unit cost reduction), and are defined in research expenditures in the KMZ model (input spillovers).

Kamien, Muller and Zang also consider another scenario, "Research Joint-Venture cartelization", where firms cooperate in R&D effort and share all information (the spillover rate is raised at its maximum) so that the constant unit cost of production decreases as the aggregate of all R&D efforts. Of course this scenario may look rather extreme since, as remarked by Martin (2002, p.462, fn 32), there is case study evidence that a firm, even though participating to an RJV, will not share all its information for strategic reasons (especially if competition is tough on the product market) or for technological or organizational reasons[10] (see De Bondt, 1996, p.4). In KMZ model, this scenario yields the highest welfare level of all since the corresponding equilibrium generates the lowest product prices and the highest per-firm profit.

This type of scenario is also used in models studying the advantage of cooperation under uncertainty. For example, Beath, Katsoulacos and Ulph (1988) analyze a "patent race" where two firms independently compete for a cost reducing innovation over time where the time of innovation is uncertain. The stochastic process is of the Poisson type and each firm strategically chooses its probability of success determining its R&D expenditure. The winner is protected by an infinitely lived but imperfect patent[11], so that, as in the previous deterministic models, the innovation also reduces the production cost of the loser (according to some given spillover rate). Alternative competition regimes in the product market are considered and affect the profit flows. Under the noncooperative scenario the R&D game has a different type of equilibrium when the spillover rate is large (imitation is easy) and when it is small (imitation is difficult). In order to compare the RJV-cartelization scenario (with spillover rate raised to its maximum) and the noncooperative scenario, two effects are in action: a positive "coordination effect" whereby firm's R&D cost is smaller under RJV, and a negative "market competition effect" coming from the fact that under RJV-cartelization all firms use fully the innovation implying more competition on the product market - and the more so the larger is the innovation and the more

[10] See De Bondt (1996, p.4) and Martin (2002, p.462, fn 32).
[11] In most other studies of cooperative R&D under uncertainty the difficulty of imitation is measured by the length of the period of protection. For an example and references to this literature see Erkal and Piccinin (2010).

competitive is the industry. When spillovers are strong, the loser's flow of profits is close to the winner's, itself close to the per-firm RJV profit flow so that the coordination effect dominates and RJV-cartelization dominates in terms of expected present value of per firm profits the noncooperative scenario. When imitation is difficult and/or competition severe[12], the per-firm RJV profit flow becomes smaller and the market competition effect dominates so that firms will not form an RJV.

3. *RJVs and Knowledge Sharing with Incomplete Information and Moral Hazard*

Much of the literature on Research Joint Ventures (RJVs), discussed above, assumes that research effort choices are coordinated, without any moral hazard (free riding) among participating firms. An exception is the paper of Kamien, Muller and Zang (1992), in which they consider a case of "RJV-competition". There, as in the case of RJV-cartelization, forming an RJV implies that its participating firms raise the spillover coefficient across their individual research efforts to its maximum, so each firm benefits fully in a deterministic way from the combined research efforts of all participants. This results in a common cost reduction accruing to all of them, for producing a substitute set of commodities on which they compete in a product market. However, each RJV participant takes its decision regarding own research effort in a non- cooperative fashion, taking others' effort levels as given, in a Nash equilibrium. They show that this leads to the lowest level of aggregate research effort among all the forms of cooperation cum coordination that they examine, owing to free riding.

[12] Clearly if product market competition is very tough, like in the Bertrand regime, a firm can only have an incentive to invest in R&D if by doing so it can gain a cost advantage.

Many of these models also have no other means of cooperation except for the effort spillovers across and coordination of effort choices among RJV participants. In particular, they do not introduce any notion of cumulative R&D, in which cooperation occurs at an earlier stage of research, followed by independently chosen development efforts. A partial exception is the paper of Grossman and Shapiro (1987), in which they consider a two stage R&D model with two firms, in which participating in the second stage requires success in the first, and earlier second-stage success leads to an exogenous strictly positive payoff, in a continuous time research race model. They consider, via numerical simulation, issues of benefits in the form of summed gains from trade across these firms at the interim stage, in two settings. In the first, of ex interim licensing, these firms do not coordinate on their research efforts in the first stage, but if (at the time point when) only one of them has succeeded in the first stage, it may choose to share its enhanced knowledge with the other firms, for a license fee, if that would raise summed profits. In the other setting, of a research joint venture, firms also coordinate on their choices of first-stage research efforts. They find that often such joint ventures decrease the firms' joint profits, owing to the more intense competition (enhanced effort choices) between them at the second stage. However, whenever interim licensing is desirable, then an RJV agreement dominates that.

Also, in all of these prior papers, there is typically no incomplete information among RJV participants about the capabilities of others in terms of their first-stage research results, which also do not affect the second stage research technology in an interior fashion, except for its feasibility. Nor is there any detailed comparison of alternative licensing rules that may induce both efficient effort choices, as well as revelation of the first stage knowledge levels attained by the set of RJV partners. In reality, these issues are often deemed important, for example in the form of qualities of own research personnel, that RJV participants contributes (depute) to their joint venture. In the presence of possibilities for their own independent first-stage research activity, such choices clearly have an impact on the extent to which knowledge gained from participants' first-stage research is shared among them.

In Bhattacharya, Glazer, and Sappington (1992), a model embodying these tradeoffs is developed, in a somewhat stylized context. It consists of three stages. In the first, each potential participant in an RJV obtains, for a fixed cost, independent draws of a "level of knowledge" from a common distribution. A higher level of this knowledge reduces the total and marginal cost of achieving any given probability of success in the second, or development stage, which is modelled as a discrete time interval or stage. These development effort levels are chosen independently by each of the RJV participants, so that an RJV is akin to the licensing only arrangement in Grossman and Shapiro (1987). However, at the end of the first stage, each of the RJV partners is only aware of its own realized level of knowledge, but not that of others. A licensing mechanism seeks to elicit full revelation, leading to sharing, of knowledge levels as well as the detailed content of such from all RJV participants. In doing so, it takes into account the impact of the structure of knowledge licensing fees on second-stage choices, in terms of the extent of development efforts chosen by participants.

Following upon success(es) in the second stage, one (or multiple) firms may gain from the new product or process in a market. To simplify matters, BGS assume that (i) the innovation is drastic, so no firm will make a positive profit competing with a successful firm using the new technology, and (ii) if there are multiple successful firms among the RJV partners, if they were to compete in the product market then they would do so a la Bertrand, and dissipate all rents in the process. The licensing mechanism of an RJV thus also seeks to eliminate such potential competition, via awarding a patent to only one among such successful partners, using a competitive auction process. This is a consequence arising from the discrete time modelling of the second stage R&D process, in which success events are independent across the firms.

The realized knowledge levels of differing firms are assumed to be ordered in a Blackwell sense, so that if these were to be all fully revealed, it would be optimal for each firm to carry out its second stage development effort using only the highest of these knowledge levels; there is no complementarity among the firms' knowledge levels, or ideas. However, each firm needs a sufficient incentive to fully disclose the content of its knowledge, as doing so may increase the efficiency of research efforts of other participating firms in the second stage, where they behave non-cooperatively. The paper characterizes licensing mechanisms which serve to elicit full disclosures.

Its optimal licensing mechanism contains three features. Identifying the firm which disclosed the highest level of knowledge; pre-specifying an ex post licensing fee that another sole successful firm in the second stage must pay this leading firm of the first stage; and running an auction among multiple successful firms in the second stage to determine who among them would obtain the right to use the intellectual property of the leading firm in the first stage in a marketable product, or process. The resulting proceeds would again be given to the first-stage leader. In addition, there may also be transfers to the first-stage (revealed) leader as a function of the level of knowledge revealed, prior to resolution of uncertainty in the second stage.

The main results in this paper are as follows. Define P*(K) as the symmetric optimal choice of its probability of second-stage success by each RJV participants for the maximum disclosed level of first-stage knowledge K, which maximizes overall expected payoffs of the RJV net of development costs. Then, specifying the ex post licensing fee the first-stage leader is paid, by a sole successful developer, at the level of its market reward from invention multiplied by P*(K), results in jointly optimal effort level choices by the RJV partners, conditional on full revelations of knowledge in the first stage. In addition, when the RJV partners can make interim transfers to the first-stage leader, which in total equal the overall expected payoff net of development cost summed across other firms, then all externalities arising from revelation of one's knowledge to second-stage rivals are internalized, inducing each RJV participant to fully reveal its first-stage knowledge. This follows as a special case of the public goods mechanism (revelation of preferences) result of d'Aspremont and Gérard-Varet (1979). Indeed, owing to the assumed Blackwell ordering of knowledge levels, the outcome is also Individually Rational conditional on each participant's realized first-stage knowledge level.

When such (potentially large) transfers are infeasible, prior to second-stage success that leads to market rewards, full disclosures of first-stage knowledge levels may arise as well in a subset of cases. These include those where the probability of second-stage success of each firm, induced by the lowest possible level of first-stage knowledge, is higher than the reciprocal of the number of firms participating in the RJV. Full revelation also arises with restricted licensing fees when the optimally chosen number of RJV participants becomes large, which happens when the fixed cost of carrying out the first-stage knowledge generation becomes small, as does expected per-firm surplus.

In d'Aspremont, Bhattacharya, and Gérard-Varet (1998), the full revelation result with unrestricted fees was extended to an analogous setting in which an RJV's participating firms' accrued knowledge levels are not ordered in a Blackwell sense, but are complementary. Conditional on full revelation, the aggregated knowledge level in an RJV is an increasing function of each participants' level of knowledge. However, the earlier type-contingent individual rationality result need not hold. In addition, in d'Aspremont, Bhattacharya, and Gérard-Varet (2000), the analysis of Blackwell-ordered knowledge levels across RJV participants was extended, to a bilateral bargaining setting under incomplete information about each other's level of knowledge, beyond common knowledge of who had the higher level of knowledge. There it is shown that – in contrast with buyer-seller bargaining over private goods in presence of asymmetric information about valuations and costs – it is possible to obtain full revelation of privately known knowledge of any level, with an interim individually rational mechanism. Indeed, all points on such a first-best Pareto frontier of sharing surplus accruing from knowledge sharing – in a non-cooperative second-stage contest or race – which assigns interior weights to the buyer's and the seller's payoffs that are independent of the level of knowledge, are incentive compatible for full revelation of knowledge. This is true both in the discrete-time development stage case discussed earlier, and when the development stage is a continuous time race for the first invention, in which the Poisson intensities of earlier invention are enhanced by a higher level of knowledge.

These results owe their origins to a basic feature of knowledge pertinent to R&D and its revelation, which differs from the usual buyer-seller game with private goods. Even though, in the absence of knowledge sharing, a firm with a higher level of knowledge has a higher expected surplus, arising from a higher probability of its second-stage success, its "competitive loss" from transferring an incremental amount of its knowledge to a second-stage rival is strictly increasing in its own knowledge level. As a result its overall objective function when it chooses how much knowledge to reveal, induced by (expected) license fees increasing in the level of its revealed knowledge, is non-concave, a property used to induce full revelation by each type.

4. *Incomplete contracts*

There is a growing literature that uses the theory of incomplete contracts[13] for the analysis of R&D. This literature analyzes situations where the quality of an innovation is observable by the R&D participants, but it is not verifiable by courts in a metric that pertains to its likely benefits. Such a setting is especially important for cumulative R&D or sequential innovation. This case is ubiquitous in the modern economy; as Scotchmer (1991, p. 24) notes, "Most innovators stand on the shoulders of giants, and never more so than in the current evolution of high technologies, where almost all technical progress builds on a foundation provided by earlier innovators." See also the Hopenhayn, Llobet, and Mitchell (2006) paper.

In the case of sequential innovation, an inventor (or a researcher, or a research unit within a corporation) produces an innovation that is then used as an input for another innovator (e.g., a large company or a development unit within a large

[13] For example see Hart and Moore 1994

company) that then develops it further and sells to the final customer. By definition, an innovation is something that is difficult to describe, so the value of this innovation – even when it is observed by both its buyer and seller – is unlikely to be verifiable by a court. This calls for the use of the incomplete contract theory. The main question in such a setup is to provide adequate incentives: both for the inventor to invest into the quality of the innovation – and for the buyer of this innovation to exert effort efficiently in developing the innovation into a final product.

The case of sequential innovation differs from the usual incomplete contract setting. Innovation is not a widget – innovation is a non-rival and (usually) a non-excludable good. Therefore, in addition to the two moral hazard problems above (incentives for research effort and for development effort) there is yet another source of potential opportunistic behavior. Upon selling an innovation, its seller (the original inventor) may actually resell the innovation to another rival buyer, who could also develop the product and then compete with the first buyer in the final market. Notice that this second sale may be ex ante suboptimal for the original seller-buyer coalition (indeed, the rent of the monopolist in the final market is higher than the joint rent of competing buyers).[14] So, if the seller were able to commit to an exclusive sale to the original buyer, she would be able to charge a higher price. The mechanisms that allow such commitment are at the center of this literature.

One simple commitment device would be patenting. If the researcher patents the original invention, and the patent is fully enforceable then the second sale can be ruled out. In this section, we consider instead the case where patents are not perfect.

[14] The second sale may or may not be socially optimal. On the one hand, it may create competition in the product market and therefore increase final customers' consumer surplus. On the other hand, if it reduces the joint surplus of the original researcher and developer, it may undermine the incentives to invest in the quality of innovation.

The other potential commitment device is vertical integration: the researcher and developer may merge into one firm with either researcher's or developer's control. Finally, there is a possibility of a 'royalty' contract – that provides the inventor with a stake in the sales of the final product of the developer (or, more generally, where the payments to the inventor are made contingent on the sales of the final product). The royalty contracts reduce incentives for a second sale, since creating competition for the original buyer of the innovation would undermine the value of the initial inventor's stake. Given the complexity of the issues above (three moral hazard problems and various assumptions on contractibility and financial constraints), it should not be surprising that there is no single comprehensive yet tractable model that covers all the aspects of sequential innovation. Instead, several influential papers focused on different trade-offs.

The first incomplete contracts paper in a context of cumulative R&D was that of Aghion and Tirole (1994). They studied the issue of vertical integration, assuming that there is only one buyer of the innovation, and thereby neglected the issue of potential leakage to a competing buyer. The main question the paper addresses is the optimal form of vertical organization. Aghion and Tirole consider two scenarios. First, there is a non-integrated case where the research unit is independent from the buyer of innovation. Second, there is vertical integration where the buyer controls the research unit.

In the integrated case, the researcher is fully expropriated and therefore has no incentives to invest; at the same time, the buyer of the innovation appropriates the entire surplus and thus has full incentives to invest. In the non-integrated case, the parties share the surplus equally, so that each has weak but non-trivial incentives.

Therefore– as in the conventional incomplete contracting literature—the authors find that the non-integrated case provides relatively stronger incentives to the seller of the innovation while vertical integration (under the control of the buyer) provides no incentives to the seller but strong incentives to the buyer. Thus, depending on the relative importance of the buyer's and the seller's investments, the parties may choose the optimal ownership structure.

The authors do not consider the third scenario where the research unit controls the downstream buyer. They argue that the research unit is likely to be financially constrained so it cannot afford acquiring the ownership of the (usually much larger) developer of the innovation. They provide yet another argument against the researcher owning the developer based on the inalienability of human capital: the developer is indispensable and cannot be forced by the researcher to develop the innovation. Interestingly, the same inalienability argument should rule out the ownership of the research unit by the buyer. Indeed, such ownership implies that research unit's human capital is alienable; in case of disagreement, the owner (the developer of the innovation) can extract the human capital and prevent the researcher herself from using the innovation. As this assumption seems too strong, the following literature has moved away from assuming direct alienability of innovator's human capital and considered alternative concepts of control rights over intellectual property, which we discuss below.

Although this has been less noticed by the follow-up literature, Aghion and Tirole's contribution goes far beyond just extending the main idea of the incomplete contracts literature, the importance of property rights for incentives, to the domain of innovation. They also consider multiple inventions and alternative customers and discuss the idea of contingent ownership (whenever there is a threat of selling to an alternative customer). They also discuss sequential innovations and trailer clause in the researcher's contracts. However, these extensions are not fully developed.

The first paper that examined sequential innovation with imperfect patents was Green and Scotchmer (1995). The authors focus on the moral-hazard-in-teams problem that is similar to the one in Aghion and Tirole (1994): the trade-off between incentives of the original inventor and sequential innovator. Their setting differs from the one described above in two ways. First, the original innovation can be improved through sequential innovation as well as marketed directly as it is. Second, they allow for the role of endogenously imperfect patents in redistributing the incentives from the first to the second innovator. They show that a broader patent (i.e. more complete protection for the original inventor) can indeed undermine the incentives of the subsequent developer. Therefore there can be a scope for a narrower patent, as the latter results in more investment in improvement. Green and Scotchmer also discuss the issue of patent length. If for a given length of a patent it is hard to resolve the moral hazard in teams problem, then a longer patent may be warranted, despite the social cost of longer patents.

In another seminal paper Anton and Yao (1994) abstract from the issues of incentives for inventing and developing the innovation, but instead focus on issues of the sale of the innovation and the opportunity of a second sale to a competing buyer. Their main result is that the threat of the second sale provides sufficient protection to the inventor so that she can prevent full expropriation by the original buyer of the innovation, and extract a substantial part of the joint surplus. The framework of their paper is very simple. There is one inventor and two potential buyers of her invention.

First, the inventor learns an (exogenous) value of her innovation. Then she (randomly) approaches one buyer. The negotiation is structured as follows. The inventor sends the buyer a message. If the innovation is valuable, the inventor can choose to reveal (or not to reveal) the nature of the innovation. If the innovation is not valuable then she cannot reveal the innovation. In response to this message, the buyer makes a take-it-or-leave-it offer (that may include royalty payments contingent on the profits or sales of the final good by the buyer). Then the inventor negotiates with the other buyer. After the negotiations are completed, the inventor chooses to which buyer she should reveal the invention (if she has not done it already).

There are two key ingredients of the model that lead to the main result. First, in the market for the final good, monopoly profits are higher than the summed profits of the duopolists, it is in the interest of the inventor to stick to an exclusive sale using the second sale only as an out-of-equilibrium threat point. Second, the buyers do not know their position in the game tree. Therefore, neither buyer can be sure whether the inventor has already accepted or rejected an offer from her competitor. Therefore, each buyer is afraid that if her offer is not good enough, the inventor will turn it down, and instead conclude an agreement with the competitor, with whom she will still have a chance to negotiate with a certain probability. This forces the buyer to offer a non-trivial share of the surplus to the inventor. If, on the other hand, they had a finite horizon perfect information game, the fact that a buyer has complete bargaining power would result in zero payoff for the inventor despite the competition between the buyers. Indeed, in this case, the second buyer would know that the inventor has already concluded negotiations with the first buyer and would therefore make an offer that would leave the inventor with zero rent. Expecting this outcome, the first buyer would also be offer a trivial payoff to the inventor.

One other important part of Anton and Yao's paper is the analysis of financial constraints. In their model, the inventor has a finite wealth of L. This allows the contracts to include not just transfers of stakes from the buyer to the inventor but also the lump-sum payments by the inventor. The paper thus establishes an important role of financial constraints as the higher the investor's wealth, the greater the contract space.

These themes above have been further developed in Bhattacharya and Guriev (2006) and Bhattacharya and Guriev (2011). In the former paper, the authors study the sale of innovation taking into account the incentives of the buyer to invest in developing the innovation into a marketable product. This creates a moral-hazard-in-teams problem but the nature of this problem is different from the one in Aghion and Tirole (1994). While in Aghion and Tirole there is a trade-off between buyer's and seller's incentives to invest in the quality of the innovation, in Bhattacharya and Guriev (2006) the trade-off modeled is that between the buyer's incentive to invest and the seller's incentive to refrain from selling the innovation to a competing buyer (in Bhattacharya and Guriev, 2006, the seller's investment in the value of a first innovation is taken as given). As in Anton and Yao, Bhattacharya and Guriev allow for royalty contracts and show that those can indeed help to sustain exclusive sale of innovation in equilibrium, at least for some parameter values. The mechanism is similar: the second sale to a competing buyer undermines the value of the inventor's stake in the first buyer's monopoly rents; therefore a substantially high royalty can create incentives for an exclusive sale. However, as giving up a stake in ex post rents to the inventor reduces the stake of the buyer herself, this undermines the buyer's own incentives to invest. The analysis implies that such a mechanism never achieves a first best outcome. Moreover, it fails to sustain an exclusive sale for some parameter values. This is the case when giving a high royalty rate to the inventor (in order to prevent the second sale) has a sufficiently strong negative effect on the buyer's incentives. The resulting value of monopoly rents themselves is reduced so much that the value of the royalties does not suffice to prevent the second sale. This logic implies that the royalty-based sale of innovation is unlikely to work for less valuable innovations.

Another important avenue of the analysis in Bhattacharya and Guriev (2006) is the comparison of the royalty-based sales with those based on patents. Certainly, if the patent system worked perfectly, it would enforce an exclusive sale. This case would be outside the scope of incomplete contract theory, which realistically assumes away perfect enforcement of contracts. Bhattacharya and Guriev instead model a situation where patents are imperfect; in order to obtain a patent, a party has to describe the innovation. Such a description inevitably leaks a part of the innovative knowledge into the public domain. Therefore, even though the inventor can sell its innovation to a single buyer (and thus reap a substantial part of the surplus), the competing buyer will also obtain a part of the innovation's value. In this case, there is no moral-hazard-in-teams problem; the buyer of innovation pays a fixed fee and is a residual claimant in developing the innovation. However, her incentives for development may again be weakened by the fact that the competing buyer receives the publicly available description of the patented innovation, and therefore can also try to develop it and, if successful, compete in the market for the final product. This mechanism is likely to outperform the royalty-based contract when leakage of information during patenting is limited and when the value of the innovation is low. See also Anton and Yao (2004) for an analysis of related tradeoffs in the context of final cost-reducing inventions.

Bhattacharya and Guriev (2011) extend this analysis in allowing for the endogenous choice of the investment by the inventor, and studying the role of financial constraints and control rights. They do not use the Aghion and Tirole's definition of control as that of the ownership of alienable human capital. Instead, Bhattacharya and Guriev suggest that control of inventor by the developer can be understood as an ex ante contract to constrain ex interim financial contracting with third parties. Such an ex interim constraint affects inventor's ex ante incentives to invest and may be optimal. This is similar to one of the major results in the mainstream incomplete contracts theory: an ex post inefficiency may help to create a commitment device and therefore strengthen the ex ante incentives. It is this result that is behind the Grossman-Hart-Moore theory of property rights. In that theory ownership means control over alienable physical capital which is complementary to human capital. Allocation of property rights affects ex post bargaining threat points, changes the division of ex post surplus and therefore has implications for ex ante incentives to invest. In Bhattacharya and Guriev's model, the role of the physical capital is played by external financial capital, which allows negotiating to a more efficient ex interim buyer-seller bargain. This is particularly the case when the realized quality of the interim innovation is low, so that a higher royalty rate is required to prevent a second sale. If the seller could make an interim payment to the buyer, aided by third-party external financing, she could still strike such a bargain, instead of getting a very imperfect patent on her innovation, which leads to a low licensing fee for revealing its full content.

Allain et al. (2011) consider a novel aspect of the interaction among these themes of vertical integration, innovation and leakage to competitors. In the paper, vertical integration results in easier dissemination of sensitive information within the integrated firm. In their model setting there are two upstream firms (suppliers) and two downstream firms who buy inputs from the suppliers, innovate and sell the final good to the customers. In the presence of vertical integration between one upstream and one downstream firm, the other downstream firm is no longer happy to buy inputs from the integrated supplier – as this may result in the leakage of her innovation to the competing downstream firm. This results in the weaker incentives for the non-integrated downstream firm to invest in innovation. Furthermore, the integrated firm responds with an even stronger investment. This results in a "foreclosure" where the vertically integrated firm crowds out independent downstream firms. Interestingly the model is set up in such a way (e.g. through assuming single sourcing) that foreclosure only takes place when there is innovation.

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