Conflict and Cooperation on R&D Markets *

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Abstract

We investigate the distribution of profits between a laboratory and two firms on the intermediate market for cost-reducing or/and demand-enhancing technology, and infer implications for the governance of R&D. The laboratory supplies tailor-made multi-dimensional R&D services at some costs, and maximizes its individual profits. Firms are interested in delegating the production of R&D services from a common laboratory, to whom they offer contingent payment offers. On the final market for goods, firms compete in prices or in quantities. We unveil mild sufficient conditions for the (non) appropriation of innovation profits by the laboratory. Anti-complementarities in the dimensions of R&D services imply that the laboratory appropriates some non-zero share of joint profits in all equilibria. In this case, we show that each firm has strategic incentives to shift to a more integrated structure by merging horizontally or by acquiring the laboratory. Complementarities in the development dimensions imply that the laboratory exactly breaks even in all equilibria. In that case, firms have no incentive to shift to a more integrated governance structure. A series of specific algebraic forms, as borrowed from the literature, illustrate the broad applicability of the results, and uncovers common features in seemingly unrelated representations of post-innovation cost and demand conditions.

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1 Introduction

License agreements and cooperative R&D have received considerable attention in the theoretical literature. One stream of research considers a monopolistic laboratory which can license a patented innovation to vertically related symmetric firms. Most contributions build on a seminal model by Katz and Shapiro (1986), in which there is complete information, the independent laboratory incurs no cost, and addresses take-it-or-leave-it offers to two downstream competitors, which are potential users of only one unit of the pre-formatted product they cannot source in-house.[1] Another stream of the literature concentrates on the comparison between non-cooperative and cooperative R&D, in terms of innovative outputs, firms' profits, and social welfare. In a pioneering paper by d'Aspremont and Jacquemin (1988), duopolistic symmetric firms invest in deterministic R&D, as supplied by a proprietary laboratory, obtain a unidimensional cost-reducing process innovation, and benefit from a knowledge externality in the form of technological spillovers. Extensions also examine non-cooperative and cooperative in-house sourcing, either in each firm's separate laboratory, or in a jointly owned laboratory with firms sharing the operating costs.[2] The literature can thus be summarized as focusing on two extreme situations: either firms close down proprietary facilities and buy the finalized licensed output of some past R&D activities from a specialized laboratory, or they share their own R&D efforts with competitors in a cooperative agreement.

The starting point of this paper is that possibilities open to firms are not limited to these polar cases. In many instances, real-world firms keep in-house resources and delegate the production of tailor-made R&D services. They contract with an independent laboratory for the completion of well specified tasks in exchange of a payment scheme.[3] Studies in the history of technology have documented this organizational choice as a long dating phenomenon that is not limited to small firms lacking internal R&D laboratories. Whereas Teece (1988, p. 257) remarks that "[d]uring the late nineteenth century and the first half of the twentieth century, American manufacturing firms bought an increasing share of R&D in-house," Mowery (1990, p. 347) observes that, "as in-house facilities grew in size and number during 1900-40, contract research institutions increasingly complemented, rather than substituted for, in-house research." For recent years, the National Science Foundation reports an amount of contracted out R&D of 6,000 in 1997, 6,710 in 1998, and 9,240 in 1999 (in millions of dollars), in the U.S. Interestingly, the data display unexplained inter-industry differences, as epitomized by the reported amount of 2,274 by only 14 firms in the pharmaceuticals industry, against a reported amount of only 101 by 104 firms in the computer and electronic products industry, for the year 1999. And for all industries, the largest firms (25,000 employees or more), which typically have proprietary facilities available, display much larger amounts of contracted out R&D than all other firm-size categories, with more than one third of the total for all three years.[4]

Beyond particularities of all kinds, a few stylized facts characterize the crux of R&D contract circumstances: (*i*) R&D is not a deterministic activity, (*ii*) R&D is a multi-dimensional activity which can yield varieties of firm-specific process or product applications, (*iii*) transfer payments addressed by firms are functions of R&D efforts as decided at the laboratory level, (*iv*) large oligopolistic firms which choose to contract for R&D services also own in-house facilities, and (*v*) have more bargaining power than independent laboratories.[5]

To the best of our knowledge, most contributions to the theoretical literature ignore these stylized facts, with the exception of two papers which focus on the first one. Aghion and Tirole (1994) and Ambec and Poitevin (2001) examine the impact of the non-deterministic character of R&D on the relative efficiency of a separated governance structure, in which a user buys an innovation from an independent unit, and an integrated structure, in which the user sources R&D internally.

Aghion and Tirole assume that an innovation is the uncertain outcome of some non contractible effort, as performed by a laboratory and financed by a user. The laboratory and the user are risk-neutral profit maximizers. In an independent structure, the laboratory owns the innovation and is endowed with the same bargaining power as the user. It first produces the innovation, and then bargains over the licence fee to receive only some share of the total returns on its effort. In an integrated structure, the user owns the innovation. The laboratory receives no reward from innovation outcomes, thus provides no effort, while the user supplies the optimal investment level. Property rights are allocated as a means of tackling the contract incompleteness problem. As a result, independence (integration) dominates if the marginal efficiency of the laboratory's effort is large (small) enough relative to the marginal efficiency of the user's investment.

Ambec and Poitevin consider also a risky innovation process, with a risk-neutral user, but with a risk-averse laboratory. They assume that contracts are complete, and introduce some informational asymmetry. If the laboratory is an independent structure, it finances the innovation from an external source, and sells it to the user. When profits are nonobservable to external financiers, the ability of the financial contract to diversify innovation risk is reduced. Alternatively, in an integrated structure, the user finances and hierarchically controls the production of the innovation in its own laboratory, before exploiting it some way. The laboratory and the user are linked by a hierarchical relationship, which is structured by an employment contract, and subject to renegotiation. It is demonstrated that the relative efficiency of the two structures depends on the correlation between the cost of developing the innovation and its market value. The independent (integrated) structure dominates when the correlation is positive (negative).

Remark that these two models fundamentally differ in their theoretical use of the non-deterministic R&D assumption. The first one emphasizes the non-contractibility of the uncertain R&D outcome. The second one stresses an informational problem as attached to the risky nature of R&D tasks. However, a common characteristic of the two models is the assumption that there is only one user. The main features of our contribution appear clearly when compared with the latter two contributions. We rule out uncertainty, and capture all other stylized facts in a common agency model. The objective is to investigate situations in which two rival firms (defined as principals) are interested in delegating the production of R&D services from a common laboratory (defined as an agent), in order to gain access to superior abilities, or to benefit from economies of scale.[6] This laboratory is independent and therefore retains complete control over all R&D effort dimensions for the supply of firm-specific innovative services. It does not benefit from any informational asymmetry and can thus appropriate innovation benefits exclusively from the competition between firms through their individual payment offers. This allows us to isolate the effect of strategic interactions between delegating firms on the size and distribution of R&D profits for classes of process or/and product multi-dimensional innovations, and with price or quantity competition on the final market. We then uncover structural conditions on the nature of R&D services, under which the choice by firms to contract out is as profitable as relying on proprietary facilities. The resulting incentives to parties to shift to a more integrated form of governance are examined in turn.

The gist of the paper is that externalities, in the supply of technology, impact the intensity of competition between potential users for the purchase of tailor-made R&D services. Two types of externalities are at play. Externalities are of the *indirect* type when the laboratory's costs are not additively separable across users. If the cost of satisfying a firm's requirements depends on the level of efforts provided to meet another firm's needs, then firms interact through their respective specifications and associated payments. Externalities can be also of the *direct* type if each firm's gross profit function depends not only on the R&D services it receives, but also on the services received by another firm. This occurs, for example, when R&D results are not fully appropriable by users, and give rise to inter-firm spillovers.[7] Intuitively, negative externalities make competition tougher (the "conflict" case), whereas positive externalities make it softer (the "cooperation" case), on the market for R&D services. Whether competition is relatively tough or soft is reflected by each firm's payment offers, and thus drives the distribution of innovation benefits between the laboratory and firms. In turn, the distribution of benefits impacts firms' incentives to merge horizontally, or to acquire the laboratory.

More specifically, we build the analysis of the interaction between the laboratory and firms on a recent theoretical contribution by Laussel and Le Breton (2001), and extensions by Billette de Villemeur and Versaevel (2002). In technical terms, this is done by associating a characterization of the highest joint profits $v(S)$, as obtained by the laboratory and a subset S of contracting firms, to the laboratory's ability to appropriate a share of total R&D benefits, and with delegating firms' equilibrium profits. We show that, when v reflects anti-complementarities in R&D dimensions, the laboratory appropriates some non-zero share of total innovation profits. Alternatively, we demonstrate that, when v reflects complementarities in R&D dimensions, the laboratory does not appropriate innovation profits. We display two sets of mild conditions, on the algebraic forms taken by the laboratory's cost function and by firms' gross profit functions, that are sufficient for either anti-complementarities or complementarities in R&D dimensions to prevail. The findings are exemplified in a series of contrasted specifications of the model, as borrowed from a variety of contributions to the industrial organization literature.

Clear implications are obtained for the industrial organization of R&D, either by an independent laboratory and distinct users, or in an integrated structure – when firms either merge horizontally, or acquire the external laboratory. It is found that, when anti-complementarities prevail, firms which delegate R&D to the laboratory have strategic incentives to shift to a more integrated form of governance. Horizontal integration of firms eliminates competition on the market for R&D services, and thus dries up the laboratory's source of profits. Vertical integration of the laboratory, with one of the two firms, permits the merged entity to ask the outsider a premium for the negative externalities it imposes by receiving R&D services. However, when complementarities dominate, delegating firms have no strategic incentive to shift to a more integrated structure, because they already appropriate all profits. This clear-cut opposition holds in the absence of efficiency gains or transaction costs, as specifically associated to particular governance structures.

The paper is organized as follows. In section 2, we specify the assumptions of a three-stage R&D delegation game. In section 3, we display two general propositions that give sufficient conditions for the (non) appropriability of (some share of) joint benefits by the laboratory. In section 4, we offer two propositions and several examples that facilitate the identification of specific algebraic forms of the laboratory's cost function, and of each firm's gross profit function, for which profits are appropriable (or not) by the laboratory. In section 5, we examine the incentives for firms to shift to a more integrated form of governance, either by merging horizontally or by acquiring the laboratory. Section 6 concludes the paper.

2 The Model

Two stages are related in a decentralized intermediate market for technology. Upstream, a set of independent laboratories supply cost-reducing or/and demand-enhancing R&D services.[8] Downstream, two firms produce and sell a (possibly differentiated) good on a final market, and maximize individual profits either in prices or in quantities. Laboratories have less bargaining power than firms, because the number of laboratories is larger than the number of firms, or firms have the capacity to source new technology from proprietary facilities. Information is complete, in the sense that firms have all relevant information, whereas the laboratory needs not to know downstream cost and demand conditions. We assume also that the two firms are interested in outsourcing R&D from the same laboratory – singularized hereafter by the subscript 0 – in order, say, to obtain economies of scale, or to tap differentiated resources. Each firm i in $N = \{1, 2\}$ is interested in controlling the selection by the laboratory of services that fit its own specificities. There are 0, 1, or 2 contracting pairs on the intermediate market for R&D. The vector $\mathbf{x} = (\mathbf{x}_1, \mathbf{x}_2)$ describes the two multi-dimensional and firm-specific R&D services supplied by the laboratory. If no firm contracts, then $\mathbf{x} = 0$; otherwise $\mathbf{x} > 0$.

We specify a common agency game, in which the laboratory (a single agent) selects the R&D

services which affect its own costs as well as the gross profits earned by the two firms (principals). In extensive form, at stage 1, the two firms $i = 1, 2$ simultaneously apply for the adoption of $\mathbf{x}_i$ by offering non-negative contingent transfers $t_i(\mathbf{x})$ in $T_i = \{t_i(\mathbf{x}) \in R^1_+ : \mathbf{x} \in X\}$ to the laboratory; at stage 2, given $\mathbf{t}(\mathbf{x}) = (t_1(\mathbf{x}), t_2(\mathbf{x}))$, the laboratory maximizes its own profits by supplying R&D services $\mathbf{x}^* = (\mathbf{x}^*_1, \mathbf{x}^*_2)$; at stage 3, given $\mathbf{x}^*$, each firm i maximizes individual profits in y_i on the final market.

Firm i's received R&D services $\mathbf{x}_i = (x^1_i, \dots, x^d_i)$ are in X_i, a sublattice of R^d_+, with $i = 1, 2$, $d \geq 1$, and $X = X_1 \times X_2$.[9] The function $f : X \to R^1_+$ represents the laboratory's costs, and is continuous in $\mathbf{x}$. The function $g_i : X \times R^2_+ \to R^1_+$ represents firm i's gross profits, and is continuous in $\mathbf{x}$ and in $\mathbf{y} = (y_1, y_2)$, with $y_i = p_i, q_i$, that is a price (Bertrand competition on the final market) or a quantity (Cournot competition). Henceforth we denote the common agency game by $\Gamma = [X, f(\mathbf{x}), \{g_i(\mathbf{x}, \mathbf{y})\}_{i=1,2}]$.

In this set-up, R&D services can lead either to a cost reduction in the production of the final good (process innovation), or/and to higher demand satisfaction for final consumers (product innovation). The nature of the innovation is reflected by the functional form of post-adoption cost and demand components, as follows.

■ **Process innovation.** The cost function is non-increasing in $\mathbf{x}_i$, all $\mathbf{x}_j, q_i$, that is $c_i(\mathbf{x}''_i, \mathbf{x}_j, q_i) \leq c_i(\mathbf{x}'_i, \mathbf{x}_j, q_i)$, for all $\mathbf{x}''_i \geq \mathbf{x}'_i$, $i, j = 1, 2$, $i \neq j$. Revenues are $r_i(\mathbf{y}_i)$, i.e. process innovations impact costs only.

■ **Product innovation.** The revenue function is non-decreasing in $\mathbf{x}_i$, all $\mathbf{x}_j, \mathbf{y}$, that is $r_i(\mathbf{x}''_i, \mathbf{x}_j, \mathbf{y}) \geq r_i(\mathbf{x}'_i, \mathbf{x}_j, \mathbf{y})$, for all $\mathbf{x}''_i \geq \mathbf{x}'_i$, $i, j = 1, 2$, $i \neq j$. Costs are $c_i(q_i)$, i.e. product innovations impact demand only.

Note that, in this paper, an innovation that results from R&D services is not limited to the latter polar cases. It can impact both cost and demand conditions.

The laboratory's net profit function is

$$v_0(\mathbf{x}) = \sum_{i \in N} t_i(\mathbf{x}) - f(\mathbf{x}). \tag{1}$$

Each firm i's net profit function is

$$v_i(\mathbf{x}) = g_i(\mathbf{x}) - t_i(\mathbf{x}), \tag{2}$$

where $g_i(\mathbf{x}) = g_i(\mathbf{x}, \mathbf{y}^*(\mathbf{x}))$ is firm i's gross concentrated profit, a function of $\mathbf{x}$, with $\mathbf{y}^*(\mathbf{x}) = (y_1^*(\mathbf{x}), y_2^*(\mathbf{x}))$. Figure 1 illustrates the set-up. Remark that, in the expressions of profits (1) and (2), all R&D costs are borne by the laboratory, whereas the production costs are incurred by firms only.[10].

[**insert figure 1 here**]

An equilibrium of Γ is described by the three-tuple $(\mathbf{x}^*, \mathbf{y}^*, \mathbf{t}^*)$. It is a Truthful Subgame-Perfect Nash Equilibrium (TSPNE), if and only if:

a) for all i, a strategy t_i^* is truthful relative to $\mathbf{x}_i^*$, that is:

$$\text{either } v_i(\mathbf{x}) = v_i(\mathbf{x}^*), \text{ or } v_i(\mathbf{x}) < v_i(\mathbf{x}^*) \text{ and } t_i^*(\mathbf{x}) = 0, \text{ all } \mathbf{x};$$

b) the pair $(\mathbf{x}^*, \mathbf{t}^*)$ is a Nash equilibrium, that is:

$$\mathbf{x}^* \in X(\mathbf{t}^*) = \arg\max_{\mathbf{x} \in X} v_0(\mathbf{x}), \text{ and}$$

$$\text{there is no } i \in N, \text{ no } t_i : X \to R_+^1, \text{ and no } \mathbf{x} \in X(t_i, t_j^*), \text{ such that } v_i(\mathbf{x}) > v_i(\mathbf{x}^*);$$

c) the vector $\mathbf{y}^*$ is a Nash equilibrium, that is:

$$v_i(\mathbf{x}^*, y_i^*(\mathbf{x}^*), y_j^*(\mathbf{x}^*)) \geq v_i(\mathbf{x}^*, y_i, y_j^*(\mathbf{x}^*))), \text{ all } y_i.$$

The concept of truthfulness can be made more intuitive by observing that it simply imposes the difference in transfer payments $t_i^*(\mathbf{x}) - t_i^*(\mathbf{x}^*)$ to exactly reflect the corresponding difference in individual gross profits, as obtained by firm i, when it receives $\mathbf{x}$ in lieu of $\mathbf{x}^*$. Bernheim and Whinston (1986) demonstrated two central properties in favour of the use of this refinement in common agency models. First, for any set of payment offers by $i = 1, 2$, the other principal j's best-response correspondence contains a truthful strategy. Therefore a principal can restrict itself to using truthful strategies. Second, all truthful Nash equilibria are coalition-proof. In this two-principal set-up, this means that total net profits, as obtained by firms in a truthful subgame-perfect Nash equilibrium, are higher than in any other subgame-perfect Nash equilibria. In this paper, all results relate to truthful subgame-perfect Nash equilibria (referred to as "equilibria" for simplicity in the following sections).

For all Γ, define the highest joint profits for the laboratory and the contracting firms

$$v_\Gamma(S) = \max_{\mathbf{x} \in X} \left(\sum_{i \in S} g_i(\mathbf{x}) - f(\mathbf{x}) \right), \tag{3}$$

where $S \in 2^N$ denotes all possible subsets of N, including the empty set. We impose $v_\Gamma(\emptyset) = 0$ (a normalization), and reckon that, for each firm, participation in the intermediate market for technology is constrained by $v_i \geq \underline{v}_i$. Remark that $\underline{v}_1, \underline{v}_2$ can be interpreted as reservation profits obtained either by sourcing substitutable R&D services from another independent and exclusive laboratory, or by relying on in-house capabilities. The latter interpretation is favoured in the following, for simplicity.[11]

We can now characterize the distribution of profits (accruing from the production of R&D services) between the laboratory and the two firms for different structural specifications of v_Γ, as follows.

3 Joint Profits Maximization and Distribution

The following two propositions establish that the laboratory's equilibrium supply of R&D services maximizes joint profits, and give the range of net equilibrium joint profits obtained by the two firms.[12]

Proposition 1 **(joint profits maximization)** *In all* TSPNE, *the R&D services* $\mathbf{x}^*$ *supplied by the laboratory are in*

$$X^* = \arg\max_{\mathbf{x}\in X} \left(\sum_{i\in N} g_i(\mathbf{x}) - f(\mathbf{x}) \right). \tag{4}$$

Proposition 1 says that, as far as the laboratory and firms are concerned, the equilibrium R&D outcome is efficient.

Proposition 2 **(joint profits distribution)** *In all* TSPNE, *profits* (v_1, v_2) *to firms are in*

$$V = \left\{ (v_1, v_2) \in R^2 : \sum_{i\in S} v_i \leq v_\Gamma(N) - v_\Gamma(N \backslash S) \text{ for all } S \in 2^N \right\}. \tag{5}$$

Proposition 2 reveals that each single firm i receives at most its marginal contribution to joint profits $v_\Gamma(N) - v_\Gamma(\{j\})$, $i, j = 1, 2$, $i \neq j$, and the laboratory appropriates the rest.

Hereafter, an R&D outcome is said to be appropriable when the laboratory obtains (some share of) the innovation benefits, that is $v_1 + v_2 < v_\Gamma(N)$, and thus $v_0 > 0$. And an R&D outcome is not appropriable when firms fully absorb innovation benefits, that is $v_1+v_2 = v_\Gamma(N)$, or equivalently $v_0 = 0$. Whether innovation benefits are appropriable or not depends on the specific forms of post-adoption gross profit functions. The following propositions describe clear-cut sufficient conditions of (non) appropriation.[13]

Proposition 3 *In all* Γ, *if* v_Γ *is strictly subadditive, that is* $v_\Gamma(N) < v_\Gamma(\{1\}) + v_\Gamma(\{2\})$, *then in all* TSPNE *R&D profits are appropriable, that is* $v_0 > 0$, *and there is a unique vector of* *equilibrium profits, that is*

$$v_i = v_\Gamma(N) - v_\Gamma(\{j\}), \qquad i,j = 1,2,\, i \neq j. \tag{6}$$

Proposition 4 *In all* Γ*, if* v_Γ *is superadditive, that is* $v_\Gamma(N) \geq v_\Gamma(\{1\}) + v_\Gamma(\{2\})$*, then in all* TSPNE *R&D profits are not appropriable, that is* $v_0 = 0$*, and all vectors of equilibrium profits are such that*

$$v_i = v_\Gamma(N) - v_j, \qquad i,j = 1,2,\, i \neq j. \tag{7}$$

The results say that the distribution of innovation benefits between the laboratory and the two firms is driven by the role of externalities in the production and diffusion of firm-specific R&D services. Proposition 3 refers to cases in which anti-complementarities (i.e., negative externalities) dominate. The strict subadditivity of v_Γ implies decreasing returns in the size of the set of users. Consequently, each firm is interested in limiting the number of other users, that is here in being the only one. Competition for the control of the choice of R&D activities is tough. This situation is favorable to the laboratory. Proposition 4 characterizes situations in which complementarities (i.e., positive externalities) prevail. The superadditivity of v_Γ implies increasing returns in the number of users. In that case, each user is interested in seeing the other firm contract also. Competition for the selection of $\mathbf{x}$ by the agent is soft. This is unfavorable to the laboratory.

Interestingly, whether v_Γ is strictly subadditive or (non strictly) superadditive can be checked by considering mild sufficient conditions on the laboratory's costs and each firm's gross profit function. We show this in the next section.

4 Applications

The objective of this section is to demonstrate the applicability of the obtained results. We offer two propositions that facilitate the identification of R&D costs and gross profits specifications for which v_Γ is either strictly subadditive or superadditive.[14]

Proposition 5 *In all* Γ*, if* $g_i(\mathbf{x}_i, \mathbf{x}''_j) \leq g_i(\mathbf{x}_i, \mathbf{x}'_j)$*, all* $\mathbf{x}''_j \geq \mathbf{x}'_j$*, and*

$$\frac{\partial^2}{\partial x_i^k \partial x_j^l} f(\mathbf{x}) > 0, \tag{8}$$

where $k, l = 1, \ldots, d$*, such that either* $i \neq j$ *or (and)* $k \neq l$*, then* v_Γ *is strictly subadditive.*

In Proposition 5, the condition on g_i describes negative *direct* externalities, and the condition on f in (8) describes negative *indirect* externalities. Although stated in terms of cross-derivatives, the latter condition can be rewritten as $f(\mathbf{x}' \wedge \mathbf{x}'') + f(\mathbf{x}' \vee \mathbf{x}'') - f(\mathbf{x}') - f(\mathbf{x}'') \geq 0$, all $\mathbf{x}', \mathbf{x}'' \in X$. Indeed, differentiability is adopted for notational convenience only, but is not required. The supermodularity condition formalizes a case of decreasing returns in R&D dimensions on the laboratory's side. Supplying more R&D services, as required by a firm, makes it more costly to serve the other firm. This can be interpreted as a phenomenon of congestion.[15]

The following examples illustrate this characterization to demonstrate that, in all cases, v_Γ is strictly sub-additive. This means that R&D benefits are appropriable, *i.e.* the laboratory earns strictly positive profits.

Example 1 □ *The vector* $\mathbf{x} = (x_1, x_2)$*, with* $X_i = \{0, 1\}$*, describes the diffusion possibilities of a patent attached to some process R&D output, with a "winner-take-all" feature. R&D cost are* $f(\mathbf{x}) = 0$ *if* $x_1 = x_2 = 0$*,* $f(\mathbf{x}) > 0$ *if* $x_1 + x_2 = 1$*, and* $f(\mathbf{x}) = +\infty$ *otherwise; a cost specification borrowed from Laussel and Le Breton* (2001)*. The function* f *is strictly supermodular in* $\mathbf{x}$*. Each firm* i*'s unit cost is a positive constant* $c_i(x_i)$*, with* $c_i(0) = c_H$ *and* $c_i(1) = c_L < c_H$*. The two firms produce a homogeneous good, compete in prices, and total demand is* $q = 1 - p$*.*

We obtain $g_i(\mathbf{x}) = (c_H - c_L)(1 - c_H) > 0$ *if* $\mathbf{x} = (1,0)$, *and* $g_i(\mathbf{x}) = 0$ *otherwise. Clearly,* $g_i(x_i, x_j'') \leq g_i(x_i, x_j')$, *all* $x_j'' \geq x_j'$. $\square$

Example 2 $\square$ *R&D costs are* $f(\mathbf{x}) = \frac{\lambda}{2}(x_1 + x_2)^2$, *and* $\lambda > 0$. *The quadratic form describes diseconomies of scale in total efforts, and the two firm-specific R&D services* x_i, $i = 1, 2$, *are perfect substitutes from the laboratory's viewpoint. It follows that* $\partial^2 f(\mathbf{x})/\partial x_1 \partial x_2 = \gamma > 0$. *Here* $X_i = [0, 1]$ *is a single-dimensional sublattice of* R_+^1. *Each user i's variable costs are normalized to zero. The algebraic form of demand is borrowed from a model by Poyago-Theotoky* (1997), *in which each "specialist" firm produces a good that can be improved on a specific technological dimension. Demand is* $q_i(\mathbf{p}, \mathbf{x}) = s\left(1 - p_j^{-1/x_j} x_j/(x_1 + x_2)\right) p_i^{-1-1/x_i}$, $i, j = 1, 2, i \neq j$, *where* $s > 0$ *measures the size of the market, and* x_i *describes a quality improvement embodied in firm i's good. Firms compete* à la *Bertrand on the product market. Then non-cooperative profit maximization leads to equilibrium prices* $p_i^*(x_i) = 1 + x_i$. *It follows that* $\partial g_j(x_j, x_{-j})/\partial x_j \leq 0$, *all* x_i, *all* s. $\square$

Example 3 $\square$ *As in the previous example, the laboratory's R&D costs are* $f(\mathbf{x}) = \frac{\lambda}{2}(x_1 + x_2)^2$, *with* $\lambda > 0$, *thus* f *is strictly supermodular in* $\mathbf{x}$, *with* $X_i = [0, c]$, $i = 1, 2$. *The two firms have variable costs* $c(\mathbf{x}, q_i) = (c - x_i - \beta x_j)q_i$, *with* $0 < c < 1$, *and* $\beta \in [0, 1]$, *as in d'Aspremont and Jacquemin* (1988). *Fixed costs are* $k = (1-c)^2/9 > 0$ *(a normalization). A perfectly homogeneous good is supplied on the final market. The inverse demand curve is* $p(\mathbf{q}) = 1 - q_i - q_j$. *Non-cooperative profit maximization in quantities leads to* $q_i^*(\mathbf{x}) = ((1-c) + (2 - \beta)x_i - (1 - 2\beta)x_j)/3$, *and to* $\partial g_i(x_i, x_j)/\partial x_j = 2q_i^*(\mathbf{x})(2\beta - 1)/3 \leq 0$, *all* x_i, *and for all* $\beta \leq 1/2$, *that is for "low" spillovers.* $\square$

All three examples demonstrate the easy applicability of Proposition 5 to various forms cost and demand specifications, in attempts to identify the strict subadditivity of v_Γ. The complementary result follows.

Proposition 6 *In all* Γ*, if* $g_i(\mathbf{x}_i, \mathbf{x}''_j) \geq g_i(\mathbf{x}_i, \mathbf{x}'_j)$*, all* $\mathbf{x}''_j \geq \mathbf{x}'_j$*, and*

$$\frac{\partial^2}{\partial x_i^k \partial x_j^l} g_i(\mathbf{x}) \geq 0, \quad \text{and} \quad \frac{\partial^2}{\partial x_i^k \partial x_j^l} f(\mathbf{x}) \leq 0, \tag{9}$$

$k, l = 1, \ldots, d$*, such that either* $i \neq j$ *or (and)* $k \neq l$*, then* v_Γ *is superadditive.*

In Proposition 6, the monotonicity condition on g_i captures a case of positive *direct* externalities. This condition is not sufficient to prove the non appropriability of innovation benefits. We need complementarities in R&D services, as described by the positive sign of the cross derivatives of g_i in the dimensions of $\mathbf{x}$. Similarly, the condition on f captures a case positive *indirect* externalities, which says that selecting a higher $\mathbf{x}$, as demanded by a firm, makes it less costly for the laboratory to satisfy the other firm. Note that, here again, differentiability is not required. The two displayed expression in (9) can be rewritten as $g(\mathbf{x}' \wedge \mathbf{x}'') + g(\mathbf{x}' \vee \mathbf{x}'') - g(\mathbf{x}') - g(\mathbf{x}'') \geq 0$, and $f(\mathbf{x}' \wedge \mathbf{x}'') + f(\mathbf{x}' \vee \mathbf{x}'') - f(\mathbf{x}') - f(\mathbf{x}'') \leq 0$, all $\mathbf{x}', \mathbf{x}'' \in X$, respectively.

Again, many possible specifications satisfy this characterization. In all examples below, v_Γ is shown to be superadditive, which means that R&D benefits are *not* appropriable, *i.e.* the laboratory exactly breaks even.

Example 4 □ *The laboratory's investment is the sum of user-specific expenditures in R&D, that is* $f(\mathbf{x}) = x_1 + x_2$*. Let* $X_i = \{0, \bar{x}\}$*, where* $\bar{x} > 0$ *is a lump-sum expenditure. Each user i's variable costs are normalized to zero, and demand is* $q_i(\mathbf{p}, \mathbf{x}) = 1/(1+\gamma) - 1/(1-\gamma^2)p_i + \gamma/(1-\gamma^2)p_j$*, where the degree of substitutability* γ *is a function of innovative efforts, as in Lambertini and Rossini* (1998)*, that is* $\gamma \equiv \gamma(\mathbf{x}) \in [0, 1]$*. R&D aims at enhancing symmetric horizontal differentiation that occurs only if the two firms buy services from the laboratory. Formally, let* $\gamma(\mathbf{x}) < 1$ *if* $x_1 x_2 > 0$*, and* $\gamma(\mathbf{x}) = 1$ *otherwise. Non-cooperative profit maximization in prices in the market stage yields* $g_i(x_i, x_j) = (1-\gamma) / (1+\gamma)(2-\gamma)^2$*, and one finds* $g_i(x_i, x''_j) \geq g_i(x_i, x'_j)$*, all* $x''_j \geq x'_j$*, and* $g_i(\mathbf{x}' \wedge \mathbf{x}'') + g_i(\mathbf{x}' \vee \mathbf{x}'') \geq g_i(\mathbf{x}') + g_i(\mathbf{x}'')$*, all* $\mathbf{x}', \mathbf{x}'' \in X$*.* □

Example 5 □ *R&D costs are* $f(\mathbf{x}) = \frac{\lambda}{2}(x_1^2 + x_2^2)$*, where* $\lambda > 0$ *captures the extent of diminishing returns in R&D on each firm-specific output* $x_i \in X_i \subseteq R_+^1$ *supplied by the laboratory. Remark that* $\partial^2 f(\mathbf{x})/\partial x_1 \partial x_2 = 0$*. Fixed costs are* $k = (1-\gamma)/((1+\gamma)(2-\gamma)^2)$ *for each user, and variable costs are zero (a normalization). Demand is* $q_i(\mathbf{p}, \mathbf{x}) = (1 + x_i + \beta x_j)/(1+\gamma) - 1/(1-\gamma^2)p_i + \gamma/(1-\gamma^2)p_j$*, where* $\gamma \in [0,1]$ *is the degree of substitutability between the two products. That is, a product innovation results in an increase of the quantity intercept, as in Jensen* (1992)*. There is Bertrand competition on the product market. Non-cooperative profit maximization leads to equilibrium prices* $p_i^*(\mathbf{x}) = (\gamma-1)(\gamma(1+\beta x_i + x_j) + 2(1 + x_i + \beta x_j))/((\gamma-2)(\gamma+2))$*. It is easy to check that* $\partial g_i(x_i, x_j)/\partial x_j \geq 0$*, and that* $\partial^2 g_i(x_i, x_j)/\partial x_i \partial x_j \geq 0$*, for all parameter values.* □

Example 6 □ *As in the previous example,* $f(\mathbf{x}) = \frac{\lambda}{2}(x_1^2 + x_2^2)$*, with* $\lambda > 0$*, thus R&D costs are weakly submodular in* $\mathbf{x}$*. Firm i's variable costs are* $c(\mathbf{x}, q_i) = (c - x_i - \beta x_j)q_i$*, with* $0 < c < 1$*, and* $\beta \in [0,1]$*, as in Example* 3 *adapted from d'Aspremont and Jacquemin* (1988)*. Firms have fixed costs* $k = (1-c)^2/9 > 0$ *(a normalization), and produce a perfectly homogeneous good. The inverse demand curve is* $p(\mathbf{q}) = 1 - q_i - q_j$*. For all* $\beta \geq 1/2$*, that is with "high" spillovers, we find* $\partial g_i(x_i, x_j)/\partial x_j = 2q_i^*(\mathbf{x})(2\beta - 1)/3 \geq 0$*, and* $\partial^2 g_i(x_i, x_j)/\partial x_i \partial x_j = 2(2\beta-1)(2-\beta)/9 \geq 0$*, in all final market equilibria.* □

5 Implications for the Governance of Innovation

The distribution of innovation benefits, which result from the production and diffusion of R&D services, can be modified either by a horizontal merger of firms, or by a shift to more a more vertically integrated structure that unifies the laboratory with one of the two firms. The existence of incentive for more integration depends essentially on the nature of competition on the market for R&D services, *i.e.* on the existence of anti-complementarities versus complementarities.

One situation, however, can be studied independently from the latter considerations, that is when the laboratory and the two firms *all participate* in some form of integration. This occurs if the laboratory acquires the two firms and controls them as subsidiaries, or if the two firms share the ownership of the laboratory and control it as a joint venture. In these cases, there is no gain in joint profits to be obtained. To see that, recall that equilibrium R&D outcomes $\mathbf{x}^*$ belong to the set of efforts which yield the highest joint profits for all parties (the joint profits maximization property). The net residual share of joint profits accruing to each buyer of another firm's equity would thus not improve on the amount of net profits received at equilibrium in the common agency game. Indeed, forward integration (i.e., the two users become subsidiaries) would imply the payment of v_i by the laboratory to the owners of downstream assets. By the same token, backward integration (i.e., the laboratory becomes a joint venture) would require the total payment of v_0 by firms for the ownership of upstream assets. The equality $v_0 + v_1 + v_2 = v_\Gamma(N)$ holds in all cases, unless further assumptions are introduced (e.g., cost or demand parameters could become a function of the governance structure). Now, if the laboratory and the two firms fully merge (i.e., the two users merge also), firms' gross profits increase because users become divisions of a two-product monopolist. However this effect is, in some sense, orthogonal to the concern of this paper. It is a consequence of a change in the final market only, that does not relate to the intermediate market for R&D services.

To conclude, one can say that strategic issues on the R&D market never provide incentives to shift to an integrated structure, in which all firms (the agent and the two principals) participate. In what follows, we study the incentives to shift to other forms of integration.

5.1 Cases of anti-complementarities

We focus in this section on all cases described in Proposition 3, in which anti-complementarities in R&D services dominate. Recall that there is a unique equilibrium, and that innovation profits are appropriable, *i.e.* the agent obtains $v_0 = v_\Gamma(N) - v_1 - v_2 > 0$, and each firm earns its marginal contribution $v_i = v_\Gamma(N) - v_\Gamma(\{j\})$.

Consider first the impact of a horizontal merger of the two firms on the distribution of joint profits. There is only one principal left on the intermediate market for technology. It does not leave any profit to the agent, so that $v_0 = 0$. In addition to gains accruing from the monopolization of the final market for goods, the positive gains to the merging parties on the market for R&D are:[16]

$$v_\Gamma(\{1\}) + v_\Gamma(\{2\}) - v_\Gamma(N) > 0. \tag{10}$$

Consider now the impact of (partial) vertical integration, where the laboratory merges with only one out of two users, say firm i. The assumption that firms can choose to source R&D services internally, by relying on proprietary resources, leads to discuss two possible cases. Assume first that firm i is endowed with superior capabilities, that is $\underline{v}_i \geq v_\Gamma(\{i\})$. Then the participation constraint $v_i > \underline{v}_i$ in the common agency game leads to $v_i = v_\Gamma(N) - v_\Gamma(\{j\}) \geq v_\Gamma(\{i\})$, by transitivity, which contradicts the strict subadditivity property. We can thus assume that the alternative case holds, in which the laboratory is endowed with superior capabilities, that is $\underline{v}_i < v_\Gamma(\{i\})$. In other words, when anti-complementarities dominate, a firm delegates the production of R&D services to a specialized laboratory only if the latter can compensate for diseconomies in the number of contracting users by offering a sufficiently high level of expertise. In this context, consider the situation in which the merged entity does not contract with the other potential user j, a situation of foreclosure. This choice does not make parties to the merger appropriate a higher level of joint profits than earned without integrating, that is $v_{0+i} = \max_{\mathbf{x}} (g_i(\mathbf{x}) - f(\mathbf{x})) \equiv v_\Gamma(\{i\})$. Indeed, the expression of individual gains $v_j = v_\Gamma(N) - v_\Gamma(\{i\})$, together with the identity $v_j = v_\Gamma(N) - v_i - v_0$, lead to the identity $v_\Gamma(\{i\}) = v_0 + v_i$. It is therefore not possible for the laboratory and a user to receive more than the reservation values v_0 and v_i, respectively, by simply merging vertically and not serving the outsider with R&D services.

[insert figure 2 here]

Assume now that, although anti-complementarities dominate, the merged entity sells R&D services to the separated user j, a situation illustrated by Figure 2. In this case, there is bilateral bargaining for the choice of $\mathbf{x}$ between the integrated party on the one side, and the outsider on the other side. The pay-off function of the merger is now given by $g_i(\mathbf{x}) - f(\mathbf{x}) + t_j(\mathbf{x})$ while the payoff function of the separated user remains unchanged as $g_j(\mathbf{x}) - t_j(\mathbf{x})$. Given the lump-sum transferability of payments, Pareto optimality of the bargaining process induces efficiency of the bargaining equilibria. In other words,

$$v_{0+i} + v_j = \max_{\mathbf{x} \in X} \left(\sum_{i \in N} g_i(\mathbf{x}) - f(\mathbf{x}) \right) \equiv v_\Gamma(N), \tag{11}$$

where v_{0+i} and v_j denote the outcome for the merged pair and the outsider, respectively, in *all* bargaining games. Moreover, we know that the integrated structure can, at a minimum, exploit the laboratory's capabilities for its own use, and insure for itself the foreclosure outcome. This guarantees that, at any equilibrium $\mathbf{x}^*$ of the bargaining process:

$$v_{0+i} = g_i(\mathbf{x}^*) - f(\mathbf{x}^*) + t_j(\mathbf{x}^*) \geq \max_{\mathbf{x} \in X} (g_i(\mathbf{x}) - f(\mathbf{x})) \equiv v_\Gamma(\{i\}). \tag{12}$$

As a result, the vertically merged entity cannot be worse-off post integration, including in the very extreme situation in which it has *no* bargaining power. Note that the latter claim implies that foreclosure is always a dominated choice for the integrated structure. The following proposition summarizes the discussion.

Proposition 7 *In all* Γ *such that* $v_\Gamma(N) < v_\Gamma(\{1\}) + v_\Gamma(\{2\})$, *and in all* TSPNE, *firms which participate by delegating R&D to the laboratory have strategic incentives to shift to a more, yet not fully, integrated form of governance. Horizontal integration allows users to extract all profits from the agent. Vertical integration permits the merged entity to ask the outsider a premium for the negative externalities it imposes.*

5.2 Cases of complementarities

We focus in this section on all cases described by Proposition 4, in which complementarities in R&D prevail. Although potential users compete for R&D services through monetary offers, which truly reflect their needs, the laboratory does not appropriate (any) innovation benefits. In all equilibria, $v_0 = 0$ and $v_i + v_j = v_\Gamma(N)$ with $v_i, v_j \geq 0$.

Clearly, since the two users already appropriate all benefits by contracting with the laboratory, and independently from final market considerations, there is no incentive to integrate horizontally on the intermediate market for technology.

Consider now the (partial) vertical integration of the laboratory with firm i only. Recall that the reservation profits $\underline{v}_i$, as obtained by relying on in-house facilities, can be more or less than $v_\Gamma(\{i\})$, as gained by firm i when it acquires the external laboratory without contracting with j, the outsider. First, assume that $\underline{v}_i < v_\Gamma(\{i\})$. In this case, firm i upgrades its expertise by merging with the external laboratory. Incentives to merge stem from the acquisition of some exogenously assumed superior ability to supply R&D outputs.[17] Of more interest is the alternative situation in which internal R&D resources are at least as efficient as the common external laboratory. To see that, assume that $\underline{v}_i \geq v_\Gamma(\{i\})$. Then consider first the situation in which the vertically integrated entity does not contract with the outsider. It obtains a payoff $v_{0+i} = v_\Gamma(\{i\})$ to be compared with $v_0 + v_i = v_i$. We know from Proposition 2 that no firm can get more than its marginal contribution to the coalition payoff, that is $v_j \leq v_\Gamma(N) - v_\Gamma(\{i\})$, and from Proposition 4 that at equilibrium $v_i = v_\Gamma(N) - v_j$. As a result:

$$v_{0+i} = v_\Gamma(\{i\}) \leq v_0 + v_i, \tag{13}$$

hence vertical integration with foreclosure, by forbidding the exploitation of positive externalities, leads merging parties to earn less than by remaining independent and participating in the agency game.[18]

Now consider the situation in which the integrated structure sells R&D services to the separate user j. Here again, a bilateral bargaining for the choice of $\mathbf{x}$, between the merged entity which receives $g_i(\mathbf{x}) - f(\mathbf{x}) + t_j(\mathbf{x})$, and the outsider which obtains $g_j(\mathbf{x}) - t_j(\mathbf{x})$, is substituted for the common agency game. At equilibrium in the bargaining game, we know that efficiency holds (in the sense of joint profits maximization), so that $v_{0+i} + v_j = v_\Gamma(N)$. The bargaining positions are such that, either by allocating R&D tasks to the acquired laboratory, or by relying on installed in-house facilities, the merged entity and the outsider can guarantee an individual payoff of at least $sup(v_\Gamma(\{i\}), \underline{v}_i) = \underline{v}_i$ and $\underline{v}_j$, respectively. To compare, at equilibrium in the agency game, we also have efficiency, that is $v_i = v_\Gamma(N) - v_j$, and we know that the participation constraints of individual firms are $v_i \geq \underline{v}_i$ and $v_j \geq \underline{v}_j$. It follows that, both in the bargaining and agency games, we have:

$$\underline{v}_i \leq v_i \leq v_\Gamma(N) - \underline{v}_j. \tag{14}$$

The set of equilibria in the common agency game is thus identical to the set of equilibria in the bargaining game. This leads to the conclusion that, unless some additional refinement is introduced that justifies the selection of distinct equilibria in the two games, firms have no incentive to integrate vertically.

Proposition 8 *In all Γ such that $v_\Gamma(N) \geq v_\Gamma(\{1\}) + v_\Gamma(\{2\})$, and in all* TSPNE*, firms which participate by delegating R&D to the laboratory have no strategic incentive to shift to a more integrated form of governance.*

6 Conclusion

This paper contributes to the understanding of the industrial organization of R&D activities. In a duopoly set-up with cost-reducing or/and demand-enhancing opportunities, we isolate the strategic interactions between firms on the market for technology. This is made possible by specifying a common agency model, in which firms delegate the production of tailor-made R&D services to the same laboratory. The model captures many stylized facts that have been ignored by the literature on license agreements or on R&D cooperation.

Our results rely on a characterization of the structure of the highest joint profit function $v_\Gamma(S)$, as earned by the laboratory and contracting firms in S. Firstly, when v_Γ reflects anti-complementarities in the dimensions of R&D services, the laboratory appropriates strictly positive profits in all equilibria (Proposition 3). By contrast, when the structural properties of v_Γ reflect complementarities in R&D dimensions, the two firms absorb all innovation profits in all equilibria (Proposition 4). We also spell out mild sufficient conditions, on the laboratory's costs and firms' gross profits functions, for the identification of structural properties of v_Γ. They make simple the determination of the laboratory's ability to appropriate or not innovation benefits, and the computation of firms' equilibrium profits (Propositions 5 and 6). The results are illustrated by a series of examples adapted from the literature. This contributes to demonstrating the broad applicability of these sufficient conditions, and also unveils structural features that are common to seemingly unrelated contributions. Of interest are the consequences of these findings for the understanding of observed modes of governance of R&D. In substance, we find that, when anti-complementarities prevail, each delegating firm has strategic incentives to shift to a more integrated form of governance, either by merging horizontally, or by acquiring the laboratory (Proposition 7). When complementarities dominate, delegating firms have no strategic incentive to shift to a more integrated form of governance (Proposition 8).

These results provide an element of explanation for observed real-world choices of governance of R&D activities. In-house sourcing is more likely to occur in cases characterized by anti-complementarities in the production and diffusion of R&D results, and separation between a laboratory and contracting firms is more likely to be observed in cases of complementarities. This claim contributes to the understanding of inter-industry differences in reported amounts of contracted out R&D, as mentionned in introduction. It is capable of empirical refutation, provided that some proxy can be identified that best describes the mentioned characterization of in terms of (anti-)complementarities.

This paper is complementary to past contributions for several reasons. Uncertainty in R&D (as considered by Aghion and Tirole, 1994; or Ambec and Poitevin, 2001) is ruled out to focus on the effect of conflicting or harmonized requirements by delegating firms on the ability of a common laboratory to appropriate a share of total benefits. Moreover, the choice of separation or integration is not assumed to impact the parametric expression of R&D costs. The model thus economizes on the reference to some exogenous factors, such as difficulties in the sharing of information between separated stages (the other side to the coin being an assumed easiness in the diffusion of knowledge in case of integration), in order to rationalize observed changes in the governance of innovation. This does not suggest that other features (including transaction costs, private information, or more bargaining power in favour of the laboratory) are not relevant for the rationalization of the real-world industrial organization of R&D activities. The present contribution has the flavour of a "floor" case, in the sense that the common agency gains, as earned by a laboratory benefitting from some informational asymmetry, should be bounded from below by the equilibrium benefits obtained here, other things remaining equal. A natural extension of the model consists in the introduction of stochastic aspects in the common laboratory's cost function.[19] We also plan to test whether the obtained results hold when there are more than two firms.[20] Another research path is to focus on a particular choice of algebraic forms, in order to compare R&D outcomes, firms profits, and welfare, as produced in the common agency set-up, with the outcomes obtained in more standard games of reference, in which firms conduct R&D tasks in-house, either non-cooperatively or cooperatively.

7 References

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Notes

[1]A series of contributions have focused the comparison of performances as obtained with alternative licensing strategies chosen by an owner of a patented cost-reducing innovation. Kamien, Oren, and Tauman (1992) compare equilibrium outcomes obtained either with a fixed fee, a per unit royalty, or the auctioning of a fixed number of licenses to firms in oligopolistic competition on a final market. By contrast, downstream strategic considerations are ignored by Bousquet, Crémer, Ivaldi, and Wolkowicz (1998), who focus on the risk sharing issue between a patentee and a single licensee under cost or demand uncertainty. Schmitz (2001) departs from the latter contributions by focusing on the effects of two downstream firms' private information about their benefits on the number of sold licenses at equilibrium. In the present model also, all relevant information is known by firms, whereas the laboratory need not know downstream cost and demand conditions. We thus adopt the informational specifications of d'Aspremont and Jacquemin (1988), and make possible the comparison of the delegated case with the non-cooperative and cooperative games of reference, without extending the complete information assumption to the laboratory.

[2]In d'Aspremont and Jacquemin (1988), cooperation in R&D augments equilibrium outputs, firms' profits, and social welfare, when technological spillovers are sufficiently high. Kamien, Muller, and Zang (1992) consider spillovers on the input side of the R&D stage. Suzumura (1992) introduces a second-best welfare criterion. Vonortas (1994) distinguishes between generic research and commercial development. Poyago-Theotoky (1999) endogeneizes spillovers. Hinloopen (2001) describes a model that encompasses most specific forms of the literature.

[3]In this paper, we interchangeably use the terms "outsourcing", "externalization", "contracting out", and "delegation", in order to refer to some "work of innovatory nature undertaken by one party on behalf of another under conditions laid out in a contract agreed formally beforehand", together with other engineering services that include design and prototyping, as in Howells (2000, p. 18).

[4]See NSF (2002, Table A10). Quoted figures refer to the industrial R&D performed outside company facilities and funded from all sources except the Federal Government. Estimates do not include industrial funding of R&D as undertaken at universities and colleges and other nonprofit organizations. The amounts of contracted out R&D for firms with 25,000 employees or more are 1,974 in 1997, 2,446 in 1998, and 3,128 in 1999 (in millions of dollars).

[5]These stylized facts are well documented by the literature at the cross-roads of economics and management science. As far as uncertainty is concerned, Jorde and Teece (1990) describe R&D as a constituent part of the innovation process, "an activity in which 'dry holes' and 'blind alleys' are the rule, not the exception" (p. 76). Helfat (1994) presents evidence from the U.S. petroleum industry in support to the claim that much corporate R&D is firm-specific, because it "often entails alterations and enhancements to existing firm assets, production processes,

and products" (p. 173). Dobler and Burt (1996) refer to the case of software development to illustrate the general observation that "R&D services normally are purchased through one of the two methods of compensation: a fixed price for a level of effort (e.g., fifty days) or a cost plus fixed or award fee" (p. 416). Using a dataset for Belgian firms, Veugelers (1997) provides evidence for know-how sourcing in proprietary laboratories and external sourcing to be simultaneously combined at the firm level, and observes that, when in-house facilities are available, "the capacity to go for it alone increases a firm's bargaining power in negotiating with external partners" (p. 304). Argyres and Liebeskind (2002) contribute to explaining the superior bargaining power of large pharmaceutical, agribusiness, and chemical firms, which tap R&D services on the intermediate market for biotechnology. The authors evoke a high rate of entry on the supply side of the market only, the resulting small size and large number of independent laboratories, the tight financial constraints they face, and their inability to enter the downstream manufacturing stage.

[6] Examples that motivate the analysis are many in the pharmaceuticals and medicines industry (in the sense of the North American Industry Classification System), for which the amounts of contracted out R&D are above all other industries. From 1993 on, Vertex, a U.S.-based private laboratory in the biotechnology sector, has signed multi-annual contracts with GlaxoSmithKline, Eli Lilly, Schering, Aventis, and Novartis, among other firms, for the completion of some well-defined R&D tasks. In the chemical industry, Symyx has signed multi-annual contracts with Bayer in 1999, and with ICI in 2000, and receives payments by providing access to a proprietary high speed combinatorial technology. The objective is to provide firm-specific R&D outputs in the form of high value speciality polymers and related applications. In the microelectronic

sector, Ovonyx was formed in 1999 and is engaged in the R&D of electrical characteristics of phase-change memory storage mechanisms. It develops and commercializes a thin-film non-volatile semiconductor memory device, a technology which can potentially be used in embedded applications in many areas, usually referred to as "system-on-chip solutions". The laboratory, which remains independent, does not only derive its income from licence fees for patented items, but also from service fees based on the development of new applications as contracted out by firms, including Intel and STMicroelectronics. In the economics and technology management literature, the exploitation of economies of scale comes on top of a list of non-mutually exclusive motivations for the external sourcing of R&D, including the resolution of a shortage in resources, the focus on core programs in-house, the opportunity to transfer fixed costs to variable costs, and the sharing of risks. For a recent survey, see Narula (2001).

[7]In the terminology of Laffont and Martimort (1997), indirect externalities are of "type 1", and direct externalities of "type 2".

[8]By referring to "services", we interpret R&D efforts as an output. However, they can be also seen as an input, that is as a pecuniary investment in several activities by the laboratory. In section 4, examples of specific algebraic forms illustrate the two possible interpretations.

[9]A set $X_i \subset R^d_+$ is a sublattice of R^d_+ if $\mathbf{x}'_i, \mathbf{x}''_i \in X_i$ implies that $\mathbf{x}'_i \wedge \mathbf{x}''_i \in X_i$ and $\mathbf{x}'_i \vee \mathbf{x}''_i \in X_i$, where $\mathbf{x}'_i \wedge \mathbf{x}''_i \equiv (\inf(x_i^{1\prime}, x_i^{1\prime\prime}), \ldots, \inf(x_i^{d\prime}, x_i^{d\prime\prime}))$ and $\mathbf{x}'_i \vee \mathbf{x}''_i \equiv (\sup(x_i^{1\prime}, x_i^{1\prime\prime}), \ldots, \sup(x_i^{d\prime}, x_i^{d\prime\prime}))$.

[10]The choice of net profit functions is similar to that considered by Crémer and Riordan (1987) for the modelling of multilateral transactions with bilateral contracts, but with transfer payments that are here contingent on the laboratory's choice of R&D services in X.

[11] Assume that firms 1 and 2 decide not to benefit from the resources of a common laboratory, and rather to source R&D services exclusively from one or the other alternative to lab 0. Then the assumption that users write contracts with complete information implies that each laboratory exactly breaks even. In that case, a firm obtains as much from the independent laboratory as it would receive by owning it.

[12] Propositions 1 and 2 are restatements of Bernheim and Whinston (1986) adapted to our context. Proofs in the notation of the present paper are available upon request.

[13] The two propositions are simple applications of a series of theorems by Laussel and Le Breton (2001). Proposition 3 results from the observation that if v_Γ is strictly subadditive, then it is not balanced. Therefore from Theorem 3.1 (p. 102) the agent obtains a rent, that is $v_0 > 0$, and from Theorem 3.3 (p. 104) we have $v_i = v_\Gamma(N) - v_\Gamma(\{j\})$, $i, j = 1, 2$, $i \neq j$. Proposition 4 results from the observation that if v_Γ is superadditive, then it is convex. It follows from Theorem 3.2 (p. 103) that in all equilibria the agent obtains no rent, that is $v_0 = 0$. Together with $v_0 + v_1 + v_2 = v_\Gamma(N)$, from Proposition 1 (joint profits maximization), this yields $v_i = v_\Gamma(N) - v_i$, $i, j = 1, 2$, $i \neq j$. The theorems, in the notation of the present, paper are available upon request.

[14] The proofs of Propositions 5 and 6 are adapted in the notation only from Billette de Villemeur and Versaevel (2002), and available upon request.

[15] Note that it can however be more profitable for the laboratory to contract with several firms.

[16] When firms shift from duopoly competition to a two-product monopoly, the merger also results in higher gains on the final market stage. This applies independently from changes that

occur on the market for technology.

[17]For empirically grounded accounts on efficiency gains as a motive for vertical integration between R&D and production stages, see Armour and Teece (1978), Pisano (1989, 1991), and Oxley (1997).

[18]Remark that we cannot have $v_i = v(\{i\})$ and $v_j = v(\{j\})$ since $v_i + v_j = v(\{1,2\}) > v(\{1\})+v(\{2\})$, by assumption. So that vertical integration with foreclosure is at most indifferent for one of the firms (and strictly worse for the other).

[19]Arguably, a model by Laussel and Le Breton (1998), with which we share most specifications, offers a natural extension to the non-deterministic case. In this model, the laboratory's cost would become $\mu f(\mathbf{x})$, where μ is a positive random variable. The agent does not know the realization of the random variable before accepting or refusing the principals' proposals (*i.e.*, strategies $t_i(\mathbf{x})$ in our notation, $i = 1, 2$), but has learned it before deciding its multi-dimensional effort level (*i.e.*, $\mathbf{x}$).

[20]The extension to the n-firm case, with $n > 2$, involves most difficulties in the case of anti-complementarities. Indeed the strict subadditivity of v_Γ, as mentioned in Propositions 3, 5, and 6, should be substituted for a more demanding characterization, namely the strong subadditivity property, as defined by Laussel and Le Breton (2001, p. 104).

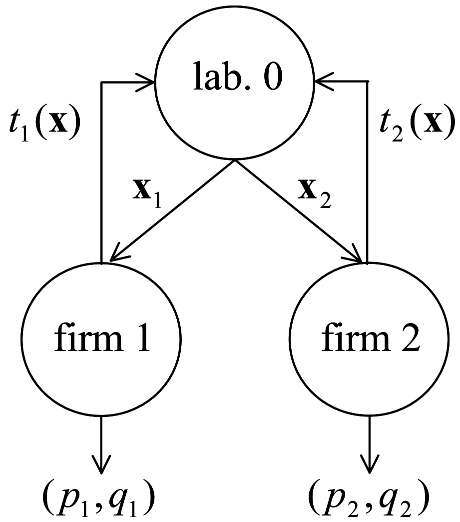

Figure 1: Firms 1 and 2 source R&D services $\mathbf{x}_1, \mathbf{x}_2$ from lab 0, in exchange of transfer payments $t_1(\mathbf{x}), t_2(\mathbf{x})$, and sell quantities q_1, q_2 at prices p_1, p_2 to earn v_1, v_2, respectively.

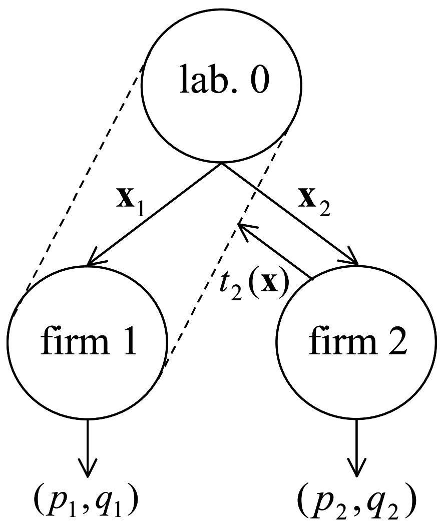

Figure 2: Firm 1 acquires the laboratory. The merged entity sells R&D services to the separate user 2.