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Abstract

The purpose of the literature on Research Joint Ventures (RJV), pioneered by D'Aspremont and Jacquemin (1988) and Kamien, Muller, and Zang (1992), has been to combine the best of two worlds: to appropriately deal with R&D spillovers while preserving competition in the product market. Moreover, RJVs eliminate duplication of R&D. Thus, at least in theory, RJVs dominate other solutions such as subsidies. If, however, we are concerned about risks of cartelization, then Spence's (1984) subsidy-based solution for independently acting firms, is a viable alternative that cannot be dismissed. Indeed, in contrast to the previous literature, we find that in the presence of R&D subsidies, market performance may unambiguously improve with the number of firms in the market.

JEL Classification: D43, L1, O32
Key Words: Research and Development, Research Joint Ventures, Process Innovation Games.

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1 Introduction

Despite the popular presumption that non-competitive behavior cannot be reconciled with welfare maximization, it has long been understood, at least since Schumpeter, that large fixed costs of R&D are incompatible with marginal cost pricing. More recently, the literature has also focused on the free-rider problem associated with R&D spillovers. However, both issues, large fixed costs and the free-rider problem, can be successfully mended with appropriate subsidies, which can restore the incentives to undertake R&D. The suggestion to alleviate the free-rider problem through subsidies was Spence's (1984), who argued that subsidy-based policy dominates patenting. He reasoned that patents are suboptimal since they assign a positive price to knowledge, when, ideally, such a public good should be priced at zero.

Indeed, in a framework where spillovers are in R&D *input* and where firms are not allowed to cooperate, Spence showed that, absent any government intervention, market performance eventually worsens as the number of firms increases. Intuitively, this seminal result is driven by the interaction of three factors: price-to-cost margins, free-riding on other firms' R&D, and duplication of R&D efforts. More specifically, as the number of firms increases, competition forces firms to price closer to marginal cost, while on the other hand, both free-riding and losses to duplication increase.

Given the presence of free-riding, this result may not seem surprising. Spence shows, however, that the free-riding problem can be solved with appropriate subsidies. Interestingly, even when free-riding is eliminated via subsidies, his result continues to hold: as the number of firms increases, duplication problems *alone* can outgrow the benefits from increased competition. This points to a fundamental incompatibility between R&D and a competitive environment when firms are not allowed to coordinate their R&D efforts.

Given this incompatibility, various solutions combining competition in the product market with cooperation in the R&D sector have been proposed. These solutions to the externality problems, such as R&D coordination or Research Joint Ventures (RJV), have been pioneered by the seminal works of D'Aspremont and Jacquemin (1988) (henceforth DJ) and Kamien, Muller, and Zang (1992) (henceforth KMZ).[1] Whereas R&D coordination alleviates free-riding by internal-

[1] The subsequent literature includes Suzumura (1992), De Bondt, Slaets, and Cassiman

izing externalities, RJVs, which are characterized by full spillovers, have the additional benefit of solving the duplication problem.[2]

This approach appears to unambiguously dominate Spence's solution since it solves all three problems simultaneously: allocative efficiency, free-riding, and duplication. However, we show that Spence's result turns out to be sensitive to the assumed R&D technology, that is, the functional form mapping R&D effort into cost reduction. In other words, the presumed incompatibility of R&D and competition among independently acting firms hinges on a critical modeling choice: we will show that for a widely used class of R&D technology, the incompatibility disappears.

The modeling choices for R&D processes may be characterized by two extreme categories: either spillovers are in R&D *input,* as is the case in Spence and KMZ, or they are in R&D *output,* as is the case in DJ. In reality, the nature of spillovers may involve a combination of both and vary among sectors. We find that, even though both technologies exhibit diminishing returns to R&D expenditures, they lead to diametrically opposite policy implications. If spillovers are in R&D *inputs,* the efficiency with which an industry achieves cost-reduction worsens as the number of firms increases. On the other hand, if spillovers are in R&D *output,* we show that the efficiency with which the industry achieves cost-reduction unambiguously *improves* with the number of firms.

This implies that if spillovers are in R&D output, combining R&D subsidies with competition would solve the incentive problems, while eliminating the trade-off between duplication and allocative efficiency. The incompatibility between competition and R&D disappears and performance unambiguously improves with the number of firms. In the absence of this incompatibility, Spence's subsidy-based solution thus becomes a viable alternative to RJVs, especially so if the latter carry with them a risk of cartelization.

The choice of R&D technology not only affects Spence's result, though, but, as we shall show later, also the analysis of alternative solutions, such as RJVs. Moreover, other modeling assumptions also

(1992), Vonortas (1994), Leahy and Neary (1997), Salant and Shaffer (1998, 1999), Amir and Wooders (1999), and Long and Soubeyran (1999a, b). For excellent surveys, see De Bondt (1997) and Martin and Scott (1998).

[2] Other options, not discussed here, include publicly provided R&D and optimal patent protection.

affect the interaction between duplication and concentration. Two important simplifying assumptions in the literature with far-reaching implications are (1) equal treatment of all firms, i.e., the restriction to symmetric equilibria and (2) constant returns to scale in the output sector. We build on an insight by Salant and Shaffer (1998, 1999), who have shown that for a wide class of two-stage models, interior and asymmetric, yet superior, equilibria may exist. In essence, constant returns to scale create a non-convexity which places the social optimum at an equilibrium that is not only asymmetric but is in fact a corner solution. It follows that the combination of symmetry and constant returns to scale assumptions defines a suboptimal benchmark against which to gauge performance. In this paper, we shall keep the constant returns to scale assumption and focus on relaxing the symmetry requirement.

Once we drop the symmetry requirement, we must distinguish between the number of R&D labs and the number of output plants: the number of plants and labs facing shut-down can differ. More specifically, we argue that in the absence of full spillovers (e.g., absence of RJVs), a social planner controlling both stages of production will play favorites and have a single plant supply the whole market in the output sector. We also find that the optimal number of labs in the R&D sector depends crucially on the chosen R&D technology. If spillovers are in R&D inputs, it is best to have all firms share a single lab, whereas under spillovers in R&D output, each firm should have its own separate lab. Conceivably, then, an optimal benchmark would involve the operation of multiple labs but only a single plant.

The previously identified benchmark, however, is not appropriate if firms are constrained to Cournot competition at the second stage, as is standard in the literature. We thus drop the social planner perspective and assume that firms are required to engage in Cournot competition in the second stage. In this new framework, the asymmetric multi-lab result when spillovers are in R&D output remains unaffected, while the single-lab result continues to hold for an important subclass of R&D technology with spillovers in R&D input.

We thus show that severe asymmetry results at both the R&D and at the output sectors, not only when firms are led by a social planner, but even when the plants must engage in Cournot competition. Therefore, unless equal treatment is enforced, the mere requirement of Cournot competition does not prevent a quasi-monopolistic outcome in the output sector: genuine competition can no longer be guaranteed. As such, the realistic implementation of RJVs may be more difficult than previously thought and policy recommendations should be revised accordingly. To maximize social welfare, regulatory agencies must ensure that all plants continue to produce since, left to their own devices, firms have a strong incentive to shut down all plants but one.

The rest of the paper is organized as follows. First we analyze the nature of the R&D process (section 2). Then we explore the ideal arrangement under an omnipotent social planner (section 3) and finally study the more realistic situation with multi-firm competition at the second stage (section 4). We conclude with policy implications of R&D in section 5.

2 Two Ways to Model the R&D Process

When studying the relative merits of policies designed to encourage R&D, simplifying assumptions, such as the restriction to symmetric equilibria, and critical modeling choices have been made. One such choice concerns the R&D technology, i.e., the functional form mapping R&D effort into cost reduction. R&D technologies can be characterized according to the nature of R&D spillovers: either spillovers are in R&D inputs, that is, in money invested (Spence and KMZ), or they are in R&D output, that is, in knowledge created (DJ).[3] While neither model is a generalization of the other, we can still place both models in a common framework and thus facilitate interpretation of the results.[4]

In the KMZ model, if firm i invests x_i dollars in R&D, the constant marginal cost of production of firm i is

$$c_i = A - f(x_i + \beta x_j), \tag{1}$$

[3] An alternative classification, provided by Beath et al. (1998), is to break the R&D process down into two stages. In the first stage, R&D investments generate knowledge, then, in the second stage, knowledge reduces the (constant) marginal cost of production. Under this interpretation, the specification common to Spence and KMZ assumes constant returns to the generation of knowledge, but decreasing returns to cost reduction. The specification in DJ, on the other hand, assumes decreasing returns in the generation of knowledge, but constant returns to cost reduction.

[4] Amir, Evstigneev, and Wooders (1999) provide a general framework of the two-stage game where they endogenize the degree of spillovers. Amir (2000) provides an excellent comparison of the two models.

where β is the spillover rate $(0 \leq \beta \leq 1)$. The R&D production function f is assumed to be both increasing and concave, to reflect diminishing returns to R&D expenditures. Here, spillovers are in R&D input.

In contrast, we will now show that in the DJ model, the constant marginal cost of production of firm i can be written as

$$c_i = A - (f(x_i) + \beta f(x_j)), \tag{2}$$

where f is increasing and concave. Hence spillovers are in R&D output. We justify the expression in equation (2) as follows: Simply let the cost of an *amount* y_i of R&D undertaken by firm i be $C(y_i) = g(y_i)$, where g is strictly convex and $g(0) = 0$ and define $h(\cdot) \equiv g^{-1}(\cdot)$. If $x_i \equiv C(y_i)$ denotes the amount of *dollars* invested in R&D by firm i, then the marginal cost of firm 1 can be written as $c_1 = A - h(x_1) - \beta h(x_2)$, where h is strictly concave since g is strictly convex. For example, as in DJ's original paper, if $C(y_i) = y_i^2 \equiv x_i$, then $c_1 = A - \sqrt{x_1} - \beta\sqrt{x_2}$.

The importance of this distinction arises out of its policy implications. Indeed, spillovers in R&D output would reverse Spence's conclusions. As mentioned in the introduction, Spence investigates, among other things, the effect of competition on market performance in a framework where firms are acting independently. A central result in Spence is that market performance eventually decreases as the number of firms, n, increases. This is due to the interaction of three factors: free riding, duplication, and allocative efficiency: as the number of firms increases, the losses from duplication and free riding outweigh the gains from allocative efficiency. Given the severity of the free rider problem, the result may not be surprising.

Spence then introduces R&D subsidies to solve the free rider problem. Surprisingly, even then, performance eventually deteriorates as n increases. Thus duplication losses *alone* outweigh the gains from allocative efficiency. This result, however, hinges on the choice of R&D technology.

In Spence's original formulation, R&D spillovers are in R&D inputs. In a symmetric equilibrium where each firm invests x/n in R&D, the constant marginal cost of each firm is given by

$$c = A - f\left(\frac{1 + \beta(n-1)}{n}x\right),$$

which, clearly, is increasing in n. Hence duplication worsens with the number of firms. In other words, the efficiency with which an industry achieves a certain amount of cost reduction worsens as n increases.

If however spillovers are in R&D *output*, as is the case in DJ, then if each firm invests x/n in R&D, then the marginal cost of each firm is given by

$$c = A - (1 + \beta(n-1))f(x/n).$$

It is straightforward to show that $\frac{dc}{dn} < 0$ if

$$\frac{f(x/n)}{x/n} > \left(\frac{1 + \beta(n-1)}{\beta n}\right) f'(x/n). \tag{3}$$

The inequality reduces to

$$\frac{f(x/n)}{x/n} > f'(x/n)$$

as $n \to \infty$. Thus for n sufficiently large, and since f is concave, the latter inequality is satisfied. Note that for some specific functions, we can get a stronger result, where inequality (3) holds for all n. For example, if $f(\cdot) = \sqrt{\cdot}$, as in DJ's original model, it is easy to show that inequality (3) will be satisfied if $\beta > 1/(1+n)$.

We therefore conclude that, if spillovers in R&D output are not too small, then the efficiency with which an industry achieves a certain amount of cost reduction *increases* with n. Since allocative efficiency increases with n as well, market performance unambiguously improves. In light of this result, Spence's subsidy-based solution becomes a viable alternative to RJVs, especially so if the latter carry with them a risk of cartelization. RJVs are studied next.

3 Social Planner and Optimal Market Structure

The dynamic models studied in the R&D literature stipulate two stages: In the first stage, each firm can invest in R&D to reduce its marginal cost of production. Because of spillovers, however, its investment also lowers, to some degree, its competitors' marginal costs. Then, in the second and final stage, and depending on the model, the firms must either engage in Cournot or Bertrand competition or they may form a cartel. The results in this literature indicate, in a nutshell,

(1) that allowing cooperation in R&D while forcing firms to compete in the output market is welfare improving – provided spillovers are large, (2) that research joint ventures dominate all the other arrangements, and (3) that the various R&D arrangements nevertheless lead to underinvestment in R&D relative to the social optimum.

The literature started by DJ (1988) has analyzed whether it is socially optimal to allow firms to form research cartels, research joint ventures (RJVs), or full cartels.[5] In the first two scenarios, firms are allowed to cooperate only in the R&D stage and must compete in the production stage. In the last scenario, firms are allowed to cooperate in both stages. In these investigations, previous studies have limited their analyses to symmetric equilibria. As such, they implicitly ruled out the possibility of corner solutions. Here we shall use an insight by Salant and Shaffer (1998, 1999) and show that if a social planner or a research cartel controls *both* stages of production, the optimum is an asymmetric equilibrium, possibly even an *extreme* equilibrium, akin to a natural monopoly, where it is best for a single firm to operate in both sectors.[6]

Before we turn to a more formal discussion, we provide some intuition for our results: suppose that a given amount of research effort x is to be allocated in amounts x_1 and x_2 between two research labs, so that $x = x_1 + x_2$. Suppose, furthermore, that we allow for asymmetry, i.e., for the possibility of one plant providing more output than the other. Then it is optimal to minimize the marginal cost of *one* plant only. Without loss of generality, let plant 1 be the chosen plant. In the KMZ case, it clearly pays off to set $x_1 = x$ and $x_2 = 0$, since $x_1 + \beta(x - x_1)$, hence $f(x_1 + \beta(x - x_1))$, is maximized at $x_1 = x$. In the DJ case, on the other hand, the concavity of f implies an interior solution in general. Thus, in DJ, even though only a single plant would be in operation, both labs would get positive, though generally uneven, funding.

[5] In both research cartels and RJVs, firms are constrained to Cournot competition in the second stage, but are allowed to maximize joint profits in choosing the level of R&D. Unlike RJVs, however, firms in research cartels do not share the results of R&D. Full cartels, finally, are not constrained to Cournot competition.

[6] Long and Soubeyran (1999a) provide a global characterization of asymmetric equilibria for two-stage games. Amir and Wooders (1998) show that R&D competition may dominate RJVs if asymmetric equilibria are considered.

3.1 Spillovers in R&D Input

When spillovers are in R&D input, such as in the Spence/KMZ framework, it is wasteful to have more than one firm in either sector.

Proposition 1 *When spillovers are in R&D input, the total cost of producing any level of output is minimized by having a single lab at the R&D stage and a single plant at the output stage.*

Proof: See Appendix.

The objective of the RJV literature has been to evaluate the combined benefits from product competition and from internalization of R&D spillovers. However, models that stipulate a cost advantage to a monopoly while simultaneously asserting the existence of multiple firms are ill-suited to analyze the benefits from RJVs among the many firms.

One may thus wonder how much of the benefits to RJVs are borne to research consolidation and how much to the restructuring of the output sector. In fact, in the KMZ case, by coordinating at the second stage and shutting down all but one plant, we can completely solve the duplication problem without involving RJVs. The violation of the *ceteris paribus* condition is an alternative explanation for why previous evaluations may be flawed: RJVs and second stage restructuring are simultaneous and their benefits cannot be dissociated and measured individually. The gains from RJVs may thus be overestimated.

3.2 Spillovers in R&D Output

In the DJ framework, there is a tradeoff between duplication of R&D efforts and diminishing returns to R&D expenditures. The following proposition shows that, independently of the degree of spillovers, it is wasteful to have more than one *plant*. It also shows that provided spillovers are not too small, it will be optimal to have multiple *labs*. Unless we have full spillovers, the labs will have different sizes.

Proposition 2 *When spillovers in R&D output are small, the total cost of producing any level of output is minimized by having a single lab in the R&D sector and a single plant at the output stage. If spillovers in R&D output are large, the total cost is minimized by having a single plant at the output stage and multiple labs at the R&D stage.*

Proof: If firm 1 invests δx and firm 2 invests $(1-\delta)x$ *dollars* in R&D ($\delta \in [0,1]$), then the marginal costs of firm 1 and 2 are given by

$$c_1(\delta) = A - h[\delta x] - \beta h[(1-\delta)x]$$

and

$$c_2(\delta) = A - h[(1-\delta)x] - \beta h[\delta x]$$

Without loss of generality let $\delta \geq 1/2$, this implies that $c_1(\delta) \leq c_2(\delta)$. Therefore, the total minimum cost of producing an arbitrary quantity of output Q, $C(Q)$, is obtained by

$$\begin{aligned} & \min_{\frac{1}{2}\leq\delta\leq 1} c_1(\delta)\cdot\left(\frac{Q}{2}+k(\delta)\right) + c_2(\delta)\cdot\left(\frac{Q}{2}-k(\delta)\right) \\ = & \min_{\frac{1}{2}\leq\delta\leq 1} c_1(\delta)\cdot Q \quad \text{since} \quad c_1(\delta)\leq c_2(\delta) \\ = & \min_{\frac{1}{2}\leq\delta\leq 1} [A - h[\delta x] - \beta h[(1-\delta)x]]\cdot Q \end{aligned}$$

To minimize $c_1(\delta)$, we should maximize $B \equiv h[\delta x] + \beta h[(1-\delta)x]$. Note that $\frac{d^2B}{d\delta^2} = x^2\left(h''[\delta x] + \beta h''[(1-\delta)x]\right) < 0$ since $h'' < 0$.

$$\frac{dB}{d\delta} = x\left(h'[\delta x] - \beta h'[(1-\delta)x]\right)$$

If $\frac{dB}{d\delta} > 0$ for any δ, then $\delta = 1$ maximizes B. This happens if $h'[\delta x] > \beta h'[(1-\delta)x]$ for any δ. A sufficient condition for this is

$$\min_{\frac{1}{2}\leq\delta\leq 1} h'[\delta x] > \max_{\frac{1}{2}\leq\delta\leq 1} \beta h'[(1-\delta)x]$$

Since h' is decreasing

$$\min_{\frac{1}{2}\leq\delta\leq 1} h'[\delta x] = h'[x]$$

Similarly,

$$\max_{\frac{1}{2}\leq\delta\leq 1} \beta h'[(1-\delta)x] = \beta h'[0]$$

Hence if $\beta \leq \frac{h'[x]}{h'[0]}$, then $\delta = 1$ maximizes B. This implies that for sufficiently small spillovers, it is cheaper to have one firm invest in R&D in the first stage and one firm produce the total output in the second stage. Similarly, if $h'[\delta x] < \beta h'[(1-\delta)x]$ for any δ, then $\delta = \frac{1}{2}$ maximizes B. A sufficient condition for this is

$$\max_{\frac{1}{2}\leq\delta\leq 1} h'[\delta x] \quad < \quad \min_{\frac{1}{2}\leq\delta\leq 1} \beta h'[(1-\delta)x]$$

$$\text{or } h'[\frac{x}{2}] \quad < \quad \beta h'[\frac{x}{2}]$$

But this is not possible since $\beta \leq 1$. Hence for $\beta > \frac{h''[x]}{h'[0]}$, an interior solution δ^* exists and satisfies the first order condition $h'[\delta^* x] = \beta h'[(1-\delta^*)x]$ or $\frac{h'[\delta^* x]}{h'[(1-\delta^*)'}$. Note that $\frac{h'[\delta x]}{h'[(1-\delta)x]}$ is decreasing in δ since $h'' < 0$. It follows that δ^* is decreasing in β. If $\beta \leq \frac{h'[x]}{h'[0]}$, then $\delta^* = 1$. If $\beta > \frac{h'[x]}{h'[0]}$, then $\delta^* < 1$ and reaches a minimum $\delta^* = \frac{1}{2}$ when $\beta = 1$. This implies that for large spillovers, it is cheaper to have two firms invest in R&D in the first stage and one firm produce the total output in the second stage. ■

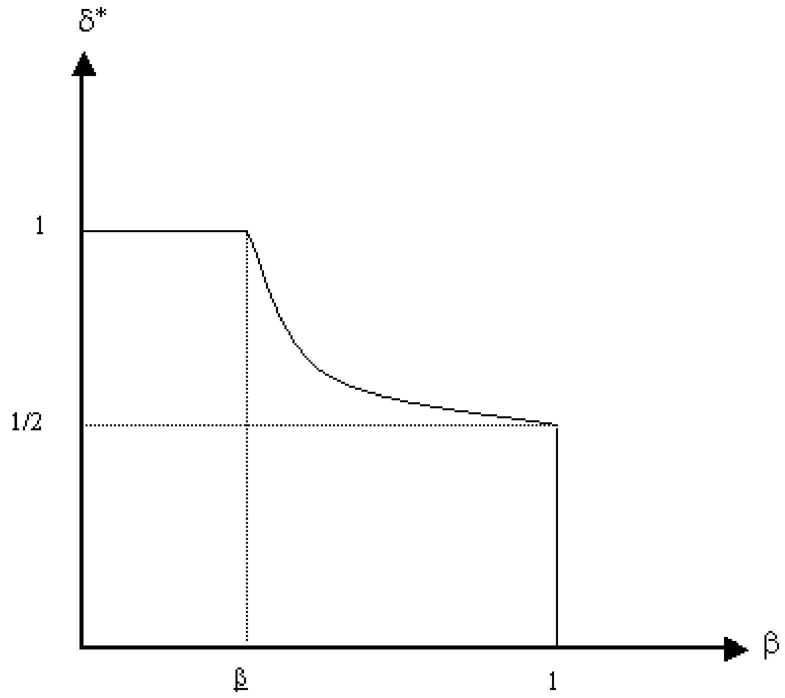

Figure 1. Optimal Allocation of R&D Investment

As shown in Figure 1, the socially optimal allocation δ^* of investments among labs is decreasing in the degree of spillovers β. Therefore, the smaller β, the more R&D efforts will be allocated to a preferred lab over all others. At one extreme, for β sufficiently low, all resources go to a single lab; at the other extreme, with full spillovers ($\beta = 1$), all labs are treated equally.[7]

Once again, we ask how much of the benefits to RJVs are borne to research consolidation and how much to the restructuring of the output sector. Note that unlike the KMZ case, RJVs are necessary to solve the duplication problem. Still, the *ceteris paribus* condition does not hold since RJVs and second stage restructuring are simultaneous. Therefore, as before, the gains from RJVs may be overestimated when there is more than one firm.

Our investigation has, so far, focused on a framework where a social planner or a cartel controls both stages of production. If, however, antitrust laws force firms to compete in the output market, we investigate a setting where firms engage in Cournot competition in the second stage output sector.

4 Competition in the Second Stage

We now focus on the RJV literature's standard framework, in which multiple firms are required to be Cournot competitors in the second stage. They are, however, allowed to cooperate in the choice of R&D investment levels so as to maximize joint profits. While we necessarily assume the existence of multiple plants, here also we drop the equal treatment requirement and look into the optimal allocation of R&D effort among the firms' various labs. Salant and Shaffer (1998, 1999) find that asymmetric equilibria can be more efficient and they provide sufficient conditions under which asymmetric investments in R&D generate not only higher industry profits *but also* a higher social surplus. We use this valuable insight to show that for an important subclass of Spence/KMZ R&D technology –specifically, for *linear* cost reducing technologies–, a *single* lab maximizes not only industry profits but also social welfare when spillovers are large. As for the DJ

[7] Amir and Wooders (1999) explore the role of the spillovers rate on intra industry heterogeneity.

model, if spillovers are large, the optimal allocation is also asymmetric, although not a corner solution.

4.1 The Basic Model

Firms now engage in Cournot competition in the second stage where the inverse demand function is given by $P = a - \sum_i Q_i$, P is the market price, and Q_i is the quantity produced by firm i.

As in the previous section, we analyze, in turn, both the Spence/KMZ and the DJ R&D technologies.

4.2 Spillovers in R&D Input

Here, we restrict our attention to a particular subclass of the KMZ-type R&D technology, namely the identity function[8], i.e., $f(x) = x$. Thus, if firm i invests x_i *dollars*, then firm i's constant marginal cost is given by $c_i = A - x_i - \beta x_j$, where $0 < \beta < 1$.

Just as in Salant and Shaffer (1998, 1999), we make use of Bergstrom and Varian's (1985) result, that in Cournot models with constant marginal costs, if the individual marginal costs are changed without altering their sum, then total industry output and price will not change *as long as* all firms continue to produce, i.e., as long as $Q_i > 0$, $i = 1, 2$. Since this implies that consumer surplus remains unaffected, it suffices to minimize aggregate production costs when either maximizing industry profit or social surplus. Using this insight, we now show that the optimal number of R&D labs is equal to one when spillovers are large.

Proposition 3 *In the model of KMZ with linear cost-reducing technology and Cournot competition in the second stage, if spillovers are sufficiently large, then the profit-maximizing, as well as socially optimal first-period arrangement for R&D, concentrates production of R&D in a single lab.*

Proof: Consider a symmetric equilibrium in R&D investment $(x/2, x/2)$ and the corresponding second stage Cournot equilibrium $Q_1 = Q_2 = Q/2 > 0$. Hence, the constant marginal cost of both firms is given by

$$c = A - \frac{x}{2} - \beta\frac{x}{2} = A - \frac{(1+\beta)x}{2}$$

[8] Our results easily generalize to affine functions, $f(x) = ax + b$.

and the total industry cost of producing Q under symmetry is given by

$$TC_s = \left(A - \frac{(1+\beta)x}{2} \right) Q$$

We now introduce asymmetry in R&D in the first stage. Let $0 \leq \delta \leq 1$ and consider asymmetric investments $(\delta x, (1-\delta)x)$. Hence, the marginal cost of firm 1 is

$$c_1(\delta) = A - \delta x - \beta(1-\delta)x$$

and the marginal cost of firm 2 is

$$c_2(\delta) = A - \beta\delta x - (1-\delta)x$$

Without loss of generality, let $\delta \geq \frac{1}{2}$, it then follows that

$$c_1(\delta) \leq c(\delta) \leq c_2(\delta)$$

The sum of the marginal costs under $(x/2, x/2)$ and $(\delta x, (1-\delta)x)$ is the same and is equal to $2A - (1+\beta)x$. Hence, Varian and Bergstrom's result applies. Therefore, it is sufficient to minimize total industry costs in order to maximize total industry profits *and* social welfare since the aggregate quantity and price remain constant.

Let $Q_1(\delta)$ and $Q_2(\delta)$ denote the Cournot equilibrium quantities. The total industry cost under asymmetry is

$$\begin{aligned}
TC_\delta &= \min_{\frac{1}{2}\leq\delta\leq 1} c_1(\delta)\cdot Q_1(\delta) + c_2(\delta)\cdot Q_2(\delta) \\
&\equiv \min_{\frac{1}{2}\leq\delta\leq 1} c_1(\delta)\left(\frac{Q}{2} + k(\delta)\right) + c_2(\delta)\left(\frac{Q}{2} - k'(\delta)\right) \\
& \quad \text{where} \quad k(\delta), \quad k'(\delta) \geq 0 \quad \text{since} \quad c_1(\delta) \leq c_2(\delta) \\
&= \min_{\frac{1}{2}\leq\delta\leq 1} c_1(\delta)\left(\frac{Q}{2} + k(\delta)\right) + c_2(\delta)\left(\frac{Q}{2} - k(\delta)\right)
\end{aligned}$$

(By Varian and Bergstrom's argument.
To use their argument, we need $k(\delta) < Q/2$
and claim that $k(\delta) = k'(\delta)$. $Q_2(\delta) > 0$, which
is shown in the appendix, guarantees that.)

$$\begin{aligned}
&= \min_{\frac{1}{2}\leq\delta\leq 1} \frac{Q}{2}\left(c_1(\delta) + c_2(\delta)\right) + k(\delta)\left(c_1(\delta) - c_2(\delta)\right) \\
&= \min_{\frac{1}{2}\leq\delta\leq 1} Q\left(A - \frac{x}{2}(1+\beta)\right) + k(\delta)\left[x(1-2\delta)(1-\beta)\right]
\end{aligned}$$

$$
\begin{aligned}
&= Q\left(A - \frac{x}{2}(1+\beta)\right) + k(1)\left[(\beta-1)x\right] \\
&\quad \text{since } \delta \geq 1/2 \text{ and } k(\delta) \text{ is increasing in } \delta \\
&< Q\left(A - \frac{x}{2}(1+\beta)\right) = TC_s \quad \blacksquare
\end{aligned}
$$

The total cost under asymmetry, TC_δ, is always smaller than the total cost under symmetry, TC_s, and achieves a minimum at $\delta = 1$, i.e. at $(x, 0)$. Recall, however, that the above argument is valid only if both plants continue to produce in the second stage Cournot game ($Q_1(\delta) > 0$ and $Q_2(\delta) > 0$), a necessary condition to apply Bergstrom and Varian's result. In the appendix we show that the condition does indeed hold, provided the degree of spillover β exceeds $1/2$.

Thus, unless firms are restricted from behaving asymmetrically, the mere requirement of Cournot competition does not prevent a quasi-monopolistic outcome in the output sector.

4.3 Spillovers in R&D Output

We now turn to the DJ specification, in which the cost of x_i units of R&D is $\gamma\frac{x_i^2}{2}$. Intuitively, asymmetry is now sufficiently costly to prevent corner solutions. Nevertheless, the allocation of R&D investment to the various labs remains asymmetric.

Proposition 4 *In the model of DJ with Cournot competition in the second stage, it is profit maximizing as well as socially optimal to spread production of R&D among multiple labs, provided spillovers are sufficiently large.*

Proof: See Appendix.

Thus under both the dictatorial first-best and Cournot's decentralized approach, asymmetry prevails. Moreover, the results are sensitive to the chosen R&D technology. In the DJ case, the result stems from a trade-off between duplication and diminishing returns to R&D investments per lab: under duplication considerations alone, a unique lab would be best, whereas diminishing returns considerations alone call for the existence of multiple, equal-sized labs. In the KMZ case, there are no such trade-offs: duplication strictly dominates and the solution is extreme.

How is the result in the DJ case to be interpreted? Assuming that a large lab can simultaneously follow diverse research paths by creating subdivisions within itself, it should be able to mimic a collection of smaller labs. In this sense, a large lab should always do at least as well as a collection of smaller labs, perhaps even more so if the small labs do not coordinate their actions. Then the coexistence of multiple labs may be attributed to the existence of a fixed factor, namely research directors. One possibility is that small labs operate independently and with their own managers. They contribute to the joint research product by supplying their own, possibly orthogonal, research. This allows for a level of diversification that could not be attained under a single R&D director.

5 Conclusion

Research Joint Ventures solve three problems associated with R&D: allocative efficiency, free-riding, and duplication. Since duplication cannot be eliminated via R&D subsidies, RJVs are, at least in theory, the best option, *independently* of the nature of spillovers. However, if we are concerned about risks of cartelization, then subsidies are a viable alternative that cannot be dismissed, especially if spillovers are large. Indeed, we showed that if spillovers are in R&D output, Spence's subsidy-based solution is fully compatible with competition.

Regarding the risks of cartelization, we showed that severe asymmetry results at both the R&D and at the output sectors, not only when firms are led by a social planner, but also when the plants must engage in Cournot competition. Thus, unless firms are restricted from behaving asymmetrically, the mere requirement of Cournot competition does not prevent a quasi-monopolistic outcome in the output sector. Firms have strong incentives to consolidate, i.e., not only to form a cartel, but also to shut down plants and research laboratories. The temptation to collude in the product market is so much stronger, because in addition to market power considerations, large cost savings can be realized. In other words, while the Cournot outcome maximizes social welfare and is locally stable, the danger is in the lure of a *pure* monopoly.

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Appendix

Proof of Proposition 1

We look at the optimal allocation of an investment of x *dollars* in R&D and the optimal allocation of an arbitrary quantity Q of output between firms to minimize the cost of producing Q. If firm 1 invests δx and firm 2 invests $(1-\delta)x$ *dollars* in R&D ($\delta \in [0,1]$), then the marginal costs of firms 1 and 2 are given by

$$c_1(\delta) = A - h[\delta x + \beta(1-\delta)x]$$

and

$$c_2(\delta) = A - h[(1-\delta)x + \beta\delta x]$$

Let $\delta \geq 1/2$, this implies that $c_1(\delta) \leq c_2(\delta)$ since $\beta \leq 1$. A similar argument applies for $\delta \leq 1/2$. Therefore, the total minimum cost of producing an arbitrary quantity Q of output is obtained by

$$\begin{aligned}
&\min_{\frac{1}{2}\leq\delta\leq 1} c_1(\delta)\cdot\left(\frac{Q}{2}+k(\delta)\right)+c_2(\delta)\cdot\left(\frac{Q}{2}-k(\delta)\right) \\
&\text{where}\quad 0\leq k(\delta)\leq Q/2 \quad\text{since}\quad \delta\geq 1/2 \\
=\ &\min_{\frac{1}{2}\leq\delta\leq 1} c_1(\delta)\cdot Q \quad\text{since}\quad c_1(\delta)\leq c_2(\delta) \\
=\ &\min_{\frac{1}{2}\leq\delta\leq 1} [A-h[\delta x+\beta(1-\delta)x]]\cdot Q \\
=\ &[A-h(x)]\cdot Q \quad \blacksquare
\end{aligned}$$

Proof of Proposition 4

As before, from (4) the cost saving from asymmetry is

$$TC_s - TC_\delta = -k(\delta)[x(1-2\delta)(1-\beta)] \geq 0$$

where $k(\delta)\geq 0$ since $\delta\geq 1/2$ and $(\frac{x}{2},\frac{x}{2})$ is the symmetric equilibrium in R&D. Now there is a cost to asymmetry in the R&D sector. The cost from asymmetry is

$$\begin{aligned}
&\frac{\gamma}{2}\left[(\delta x)^2+(1-\delta)^2x^2-[(x/2)^2+(x/2)^2]\right] \\
=\ &\frac{\gamma}{2}\left(2\delta^2-2\delta+\frac{1}{2}\right)x^2
\end{aligned}$$

Define $L(\delta)$ as the net loss from asymmetry:

$$L(\delta) = k(\delta)[x(1-2\delta)(1-\beta)] + \frac{\gamma}{2}\left(2\delta^2-2\delta+\frac{1}{2}\right)x^2$$

If $L(1)>0$, then the symmetric equilibrium is better than having one firm in R&D.

$$L(1) = -k(1)x(1-\beta)+\gamma\frac{x^2}{4}$$

$L(1)>0$ requires that

$$k(1) < \frac{\gamma x}{4(1-\beta)}$$

We showed above that if $\beta>1/2$, $Q_2(1)=Q/2-k(1)>0$ and hence $k(1)$ is bounded above by $Q/2$

$$k(1) < \frac{Q}{2} = \frac{a-A}{3}+(1+\beta)\frac{x}{6}$$

Therefore, a *sufficient* condition for $k(1)$ to be less than $\frac{\gamma x}{4(1-\beta)}$ is

$$\frac{a-A}{3} + (1+\beta)\frac{x}{6} \leq \frac{\gamma x}{4(1-\beta)}$$

or

$$x \geq \frac{8\,(a-A)\,(1-\beta)}{6\gamma - 4(1-\beta^2)} \tag{4}$$

Note that the right hand side of (4) is decreasing in β.
It is straightforward to show that

$$\frac{x}{2} = \frac{(\beta+1)(a-A)}{4.5\gamma - (\beta+1)^2}$$

Hence, the left hand side of (4) is increasing in β. Let β^* be s.t. (4) is satisfied with equality. Then for $\beta > \beta^*$, (4) will be satisfied. Hence if $\beta \geq \max\{\frac{1}{2}, \beta^*\}$, it is optimal to have more than one firm in the R&D sector. ■

Proof that the Cournot Quantities are Positive

Given (x_1, x_2), the Cournot equilibrium quantities in the second stage are given by

$$Q_1(x_1, x_2) = \frac{(a-A) + (2-\beta)x_1 + (2\beta-1)x_2}{3}$$

and

$$Q_2(x_1, x_2) = \frac{(a-A) + (2-\beta)x_2 + (2\beta-1)x_1}{3}$$

Let $(x_1, x_2) = (\delta x, (1-\delta)x)$ then we have

$$\begin{aligned} Q_1(\delta) &= \frac{(a-A) + (2-\beta)\delta x + (2\beta-1)(1-\delta)x}{3} \\ &= \frac{(a-A) + 3\delta x(1-\beta) + x(2\beta-1) > 0}{3} \end{aligned}$$

Note that $Q_1(\delta)$ achieves a minimum at $\delta = \frac{1}{2}$.

$$Q_1|_{\delta=\frac{1}{2}} = \frac{(a-A) + \frac{x}{2}(\beta+1)}{3}$$

Hence $Q_1(\delta) > 0$ for any $\delta \geq \frac{1}{2}$. For firm 2, $Q_2(\delta)$ is given by

$$\begin{aligned} Q_2(\delta) &= \frac{(a-A) + (2-\beta)(1-\delta)x + (2\beta-1)\delta x}{3} \\ &= \frac{(a-A) + x\left((2-\beta) + 3\delta(\beta-1)\right)}{3} \end{aligned}$$

Note that $Q_2(\delta)$ achieves a minimum at $\delta = 1$.

$$Q_2|_{\delta=1} = \frac{(a-A) + x(2\beta-1)}{3}$$

Hence a sufficient condition for $Q_2(\delta) > 0$ is $\beta > 1/2$.