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R&D AS A PRISONER'S DILEMMA AND R&D-AVOIDING CARTELS*

by
RABAH AMIR
University of Arizona
FILOMENA GARCIA
ISEG/Technical University of Lisbon and UECE—Research Unit on Complexity and Economics
CHRISTINE HALMENSCHLAGER
ERMES, Université Paris II
and
JOANA PAIS†
SEG/Technical University of Lisbon and UECE—Research Unit on Complexity and Economics

Duopoly firms engaged in a standard two-stage game of R&D and Cournot competition are caught in a prisoner's dilemma for their R&D decisions whenever spillover effects are low. This effect works to the advantage of consumers and society. This result provides an interesting perspective on the well-known wedge between private and social incentives for R&D. The prisoner's dilemma is the key effect behind this wedge under low spillovers. The latter take over when sufficiently high, as is widely recognized. This mutually exclusive nature of the prisoner's dilemma and significant spillovers also serves to explain the incentives to form R&D cartels.

1 Introduction

R&D competition between firms is seldom, if ever, explicitly viewed as a prisoner's dilemma. Yet, upon second thought, the idea surely sounds plausible enough, in the sense that firms might in some circumstances feel compelled by strategic forces to engage in process R&D, when the *status quo ante* or the pre-R&D situation might actually be to their joint advantage, without being immune to a unilateral decision by each of the firms to engage in R&D. In other words, firms might sometimes conduct R&D with the sole intent of keeping up with their rivals, knowing full well that they essentially have no real choice in the matter. Simply put, it might be the only way for a firm that is fully aware of its strategic environment to survive and continue operating

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in the market, rather than a promising way to forge ahead of its rivals and expand its market share in any sustainable manner.

This paper is an attempt to investigate the scope for this interesting possibility within a standard symmetric two-period framework of duopolistic process R&D/Cournot competition with spillover effects, according to a version due to d'Aspremont and Jacquemin (1988), hence-forth AJ. Since this setting differs markedly from the familiar 2×2 game, some qualifications are needed. The prisoner's dilemma will be understood throughout to refer only to the R&D decisions taken in the first stage, with the corresponding pay-off functions reflecting the unique Cournot equilibrium in the second stage. In addition, as R&D decisions are postulated as usual to lie in a real interval, we argue that one meaningful definition of a prisoner's dilemma in this context is to require the decisions of no R&D by both firms to Pareto dominate the symmetric non-cooperative equilibrium pay-offs in AJ, in addition to the fact that zero R&D is itself a serially dominated strategy for each firm.

As this model posits additive spillovers in R&D outputs or cost reductions, it turns out that each player's profit is increasing in rival's R&D level whenever the spillover rate is above 50 per cent. In the latter case, it is easy to show that a prisoner's dilemma in R&D cannot possibly hold. However, when the spillover rate is below 50 per cent, we find that a prisoner's dilemma in R&D indeed prevails whenever spillovers are low enough, so that in no case can this situation hold when the spillover rate exceeds 20 per cent. There is also an inverse dependence of the scope for a prisoner's dilemma on the level of R&D costs, which is intuitively plausible since a higher cost of R&D directly implies a lower propensity on the part of firms to engage in R&D, and thus indirectly leads to a narrower scope for the prisoner's dilemma effect.

A prisoner's dilemma always tends to constitute bad news for the players that are caught in it. In the present context, while R&D competition will tend to ruin the firms involved in it, it can hopefully work to the benefit of society as a whole. Indeed, a simple (second-best) welfare analysis on the AJ model confirms this intuitive point: the prisoner's dilemma at hand is always beneficial to consumers, so much that it works out to be to the advantage of society as a whole too.

A virtual consensus exists on the importance of one key feature of R&D, the near-ubiquitous presence of imperfect appropriability, also often referred to as knowledge externalities or spillovers.[1] The present characterization of a prisoner's dilemma in R&D can shed some light on the effects of imperfect appropriability of R&D. Indeed, under low spillovers, firms' R&D behavior is only mildly affected by the public goods externality but conditioned by the powerful grip of the prisoner's dilemma at hand, while at high spillovers, the well-known knowledge externality is the lone impediment to firms' well-

[1]As succinctly summarized in a survey article by Griliches (1995), '. . . R&D spillovers are present, their magnitude may be quite large and social rate of return remain significantly above private rates.'

being. Thus, substantial imperfect appropriability and the R&D prisoner's dilemma may be viewed as (mutually exclusive) substitutes in bringing firms' profits down. This suggests that mid-level spillovers might be preferred by the firms to either low or high spillovers, which is indeed the case. As shown by De Bondt *et al*. (1992), per-firm equilibrium profit in this two-stage game is known to be inverse U-shaped in the spillover rate, with the maximum lying above a spillover rate of 50 per cent. As for social welfare, although it is always enhanced by the prisoner's dilemma as noted earlier, its qualitative dependence on the spillover rate is the same as for profits, i.e. inverse U-shaped, as shown also in the latter study. In the way of intuition for the latter result, we simply observe that the dependence of welfare on the spillover rate closely mirrors that of the effective equilibrium R&D level (i.e. the sum of own plus spilled over R&D), which increases up to its maximum at 50 per cent spillover and then decreases (Amir, 2000a).

The recent extensive literature on R&D cooperation may be viewed as building on Schumpeter's (1943) early work on the relationship between market structure and innovation, by broadening the concept of market structure to include hybrid markets wherein firms collaborate in some form on the conduct of R&D while remaining competitors in the product market.[2] While R&D cartels between market-competing firms are obviously profitable to firms, this literature has demonstrated that they are often advantageous to society and even to consumers.

The prisoner's dilemma result can also be invoked to provide a clarifying perspective on the incentives firms face for forming R&D cartels, as an alternative to non-cooperative R&D. These incentives are very strong when spillover rates are either close to 0 per cent or close to 100 per cent, but very weak for mid-level spillovers (and totally absent when the spillover rate is exactly 50 per cent). Under high spillovers, forming an R&D cartel would be a classical way of internalizing the large knowledge externality, as is widely recognized (see, for example, Bernstein and Nadiri, 1988). On the other hand, under low spillovers, going for an R&D cartel would be a way out of the ruinous prisoner's dilemma grip. By forcing firms to engage in R&D they would jointly rather avoid, this prisoner's dilemma works to the advantage of both consumers and society. This suggests that antitrust authorities should consider a more discriminating policy towards R&D cartels, which would be less favorably disposed towards them in industries with low spillovers.

A direct implication of the presence of a prisoner's dilemma in R&D is that firms may be tempted to engage in a simple form of cartel agreement, as an alternative to non-cooperative R&D: commit *vis-à-vis* the rival not to conduct any R&D. Since this new type of arrangement would only be appeal-

[2]There is a very rich literature on this topic (see Ruff, 1969; Spence, 1984; Katz, 1986; AJ; Kamien *et al*., 1992; Katsoulacos and Ulph, 1998; Amir, 2000a; Martin, 2002; Piga and Poyago-Theotoky, 2005, among others).

ing to firms when spillovers effects are small, it might serve as a substitute to a standard R&D cartel, which is usually thought of as being more appropriate for firms when spillovers are substantial (see, for example, AJ). One key difference is that a no-R&D agreement probably falls outside the scope of permitted R&D cooperation by antitrust authorities. Instead, since its sole aim is to curtail spending on process R&D, it is invariably detrimental to consumers, and thus likely to be considered as being under the scope of standard anticollusion legislation.

This paper is organized as follows. Section 2 summarizes the basic AJ model and its main results of interest to the present paper. Section 3 provides a characterization of the parameter region under which a prisoner's dilemma holds, along with the associated welfare analysis. Section 4 discusses the no-R&D cartel. Section 5 briefly concludes.

2 The AJ Model

This section examines the most commonly used framework for non-cooperative R&D in duopoly with spillovers by means of a simple two-stage model, in the specific version introduced by AJ.[3]

Consider the following two-stage game. At the beginning of stage 1, both firms have a common *initial* marginal cost c such that $c < a$. Then, firms simultaneously decide on cost reduction levels x_i so that the actual marginal cost of firm i changes into $\max\{c - x_i - \beta x_j, 0\}$, where $0 \le \beta \le 1$ and $i, j = 1, 2$, $j \ne i$. Here, β is a spillover parameter that captures the degree of involuntary (and unavoidable) leakage of private R&D results from a firm to its market rival. Following AJ, the cost of acquiring a cost reduction x_i is given by $\gamma x_i^2/2$, where $\gamma > 0$ can be thought of as a measure of the cost of R&D. Clearly, the R&D technology is characterized by decreasing returns to scale. In stage 2, upon learning the R&D decisions (and thus the new unit costs), the two firms engage in Cournot competition in a homogeneous-good market with inverse demand $P(q_1 + q_2) = a - b(q_1 + q_2)$, where $b > 0$ and q_1 and q_2 are the outputs of firms 1 and 2, respectively.

We refer to the above benchmark case as Case N, with N standing for non-cooperative R&D. In this scenario, firms decide on their private cost reduction levels in a fully non-cooperative way (while being aware of the underlying spillover effects) and then engage in Cournot competition given the resulting marginal costs. Throughout the paper, we concentrate on subgame-perfect equilibria of the two-stage game.

The profit function of firm 1 (say) as a function of the two R&D levels, conditional on the subsequent second-stage Cournot equilibrium, is[4]

[3]More recent work on the same topic includes Salant and Shaffer (1998), Hinloopen (2000a, 2000b), Hauenschild (2003), Jin and Troege (2006) and others.

[4]This uses the well-known fact that the Cournot equilibrium profit of firm 1, say, in a duopoly with linear demand and unit costs c_1 and c_2 is $(1/9b)(a - 2c_1 + c_2)^2$.

$$\pi_1(x_1,x_2) = \frac{1}{9b}[a-2(c-x_1-\beta x_2)+(c-x_2-\beta x_1)]^2 - \frac{1}{2}\gamma x_1^2$$
$$= \frac{1}{9b}[a-c+(2-\beta)x_1-(1-2\beta)x_2]^2 - \frac{1}{2}\gamma x_1^2 \qquad (1)$$

It represents the pay-off of firm i as a function of private cost reduction levels. In stage 1, firm i chooses an element of $A_i \triangleq \{x_i : x_i \leq c - \beta x_j\}$ in order to maximize $\pi_i(x_i,x_j)$, taking x_j as given, $i, j = 1, 2, j \neq i$. The definition of A_i reflects the fact that any $x_i > c - \beta x_j$ is a dominated action for firm i.

Since the market stage has a unique Cournot equilibrium, to every Nash equilibrium of the R&D stage with pay-offs given by (1) corresponds a subgame-perfect Nash equilibrium of the two-stage game, and vice versa. In view of this equivalence, in the remainder we will refer to the Nash equilibrium of the game with pay-offs (1) only. With a slight abuse of terminology, we shall also refer to the latter game simply as the R&D game for convenience.

Following the bulk of the literature spurred by AJ, we assume the standard second-order condition (to be referred to as SOC below)

$$9b\gamma > 2(2-\beta)^2 \qquad (2)$$

holds, in which case each firm's pay-off is strictly concave in own R&D level for each fixed rival's R&D level.

Firm i's reaction function in the R&D game is given by

$$r_i(x_j) = \min\{x^*(x_j), c - \beta x_j\}$$

where $x^*(x_j)$ denotes the unique root of $\partial\pi_i(x_i,x_j)/\partial x_i = 0$.

Leaving out all computational details, the game under consideration has a unique symmetric equilibrium[5] where each firm obtains private cost reduction

$$x_{\mathrm{N}} = \begin{cases} \dfrac{2(2-\beta)(a-c)}{9b\gamma - 2(2-\beta)(1+\beta)} & \text{if } 9b\gamma > 2(2-\beta)(1+\beta)\dfrac{a}{c} \\ \dfrac{c}{1+\beta} & \text{if } 9b\gamma \leq 2(2-\beta)(1+\beta)\dfrac{a}{c} \end{cases}$$

and per-firm profit in the two-stage game is equal to

$$\pi_i(x_{\mathrm{N}},x_{\mathrm{N}}) = \begin{cases} \dfrac{\gamma(a-c)^2\left[9b\gamma - 2(\beta-2)^2\right]}{[9b\gamma - 2(2-\beta)(1+\beta)]^2} & \text{if } 9b\gamma > 2(2-\beta)(1+\beta)\dfrac{a}{c} \\ \dfrac{a^2}{9b} - \dfrac{\gamma c^2}{2(1+\beta)^2} & \text{if } 9b\gamma \leq 2(2-\beta)(1+\beta)\dfrac{a}{c} \end{cases}$$

[5]This equilibrium is stable under best reply dynamics only if $b\gamma > 2(2-\beta)(1-\beta)/3$. For smaller $b\gamma$, there are two other asymmetric and locally stable equilibria in which one of the two firms obtains a complete reduction of marginal costs. See, for instance, Amir and Wooders (1998) and Tesoriere (2009).

In both of the above equilibrium quantities, the first line reflects an interior cost reduction, i.e. one satisfying $x_N < c/(1 + \beta)$ in view of the presence of spillover effects, while the second reflects a boundary equilibrium cost reduction, i.e. $x_N = c/(1 + \beta)$. Unlike much of the literature on the topic, we shall keep track of this distinction throughout this paper.[6]

3 The R&D Game as a Prisoner's Dilemma

In this section, we investigate the extent to which the presence of deterministic cost-reducing opportunities might constitute bad news rather than good news for the firms in the industry under consideration. Competitive forces in such markets might be such that each firm might find it to its unilateral advantage to conduct some amount of R&D, but that collectively the firms would be better off simply ignoring the R&D opportunities altogether, in the sense that their Cournot profits would actually improve in the latter case. However, this joint improvement in profits is not consistent with subgame-perfect equilibrium play for the two-stage game. Rather it is possible only as a collusive outcome of the R&D game. We emphasize that collusion is meant here only with respect to R&D decisions, as the firms are assumed to remain Cournot competitors in the product market competition throughout this paper.[7]

In what follows, we first compare the equilibrium per-firm profit under Case N with the profit that firms would achieve if they (collusively) refrained from engaging in any R&D. We then compare the social welfare levels associated with these two possible outcomes.

3.1 Profit Comparison

Throughout this paper, the following common assumption about the size of market demand is maintained.

Assumption 1: $a > 2c$.

Assumption 1 guarantees that both firms are active in the market stage, in the sense of producing a strictly positive Cournot equilibrium output, irrespective of the levels of R&D chosen by both firms (in other words, this guarantees that even a full cost reduction by one firm cannot constitute a drastic innovation in the present context).

It is well known that, for this model, due to the fact that the R&D cost function is quadratic, the marginal cost of R&D at zero is always zero. Since

[6]In view of this separation between interior and boundary equilibria, the tacit natural assumptions (not made explicit so far) in (1), that $c - x_1 - \beta x_2 \geq 0$ and $c - x_2 - \beta x_1 \geq 0$, are automatically satisfied.

[7]The postulate that firms may collude in R&D while continuing to compete on the product market is consistent with antitrust regulation in most industrialized countries nowadays. Most of the literature on R&D cooperation follows this formulation.

the marginal revenue of R&D at zero is strictly positive, a firm will never find it optimal to conduct zero R&D, irrespective of the level of R&D its rival chooses in Case N. In other words, zero R&D is never a best response to anything the rival might do. To see this, consider the first-order condition of firm 1 (say) in the R&D game

$$\frac{\partial \pi_1(x_1, x_2)}{\partial x_1} = \frac{2(2-\beta)}{9b}[a - c + (2-\beta)x_1 - (1-2\beta)x_2] - \gamma x_1$$

Hence, in view of Assumption 1,

$$\frac{\partial \pi_1(0, x_2)}{\partial x_1} = \frac{2(2-\beta)}{9b}[a - c - (1-2\beta)x_2] > 0 \qquad \text{for all } x_2 \in [0, c]$$

This shows that, in the AJ specification, a firm would never respond with zero R&D to any R&D level the rival might choose. It follows that the strategy of zero R&D is not part of the set of R&D levels that survives the process of iterative elimination of strictly dominated R&D strategies for the game with pay-offs given by (1).[8]

If, in addition to the above property for the strategy of zero R&D for each firm, we have that, for the game with pay-offs given by (1), action pair (0,0) for the R&D choices yields pay-offs that Pareto dominate the Nash equilibrium pay-offs, i.e. those corresponding to conducting the Nash equilibrium levels of R&D, i.e. if

$$\pi(0,0) > \pi(x_N, x_N) \tag{3}$$

we shall say that the R&D game has a prisoner's dilemma flavor.

As the game with pay-offs given by (1) features a continuum of actions for each player, to the best of our knowledge, there is no universal definition for what might constitute a prisoner's dilemma, but the above two critical requirements are arguably among the most salient properties for any plausible definition. Relative to the standard case of a binary action game, the R&D game in the present setting does not satisfy the property that the Nash equilibrium is in dominant strategies. However, the latter property is clearly far more demanding in the context of a game with a continuum of actions, where it is only satisfied in non-robust or degenerate cases.[9] For instance, for the R&D game at hand, a dominant strategy equilibrium prevails if and only if $\beta = 1/2$, which is obviously a knife-edge special case.[10]

To recapitulate, given that not conducting any R&D is an (iteratively) dominated strategy for each firm, firms may be thought of as being caught in

[8]As a consequence, the choice of zero R&D for a firm can never have strictly positive probability in any mixed-strategy Nash equilibrium or correlated equilibrium. For details on the properties of iterative elimination of strictly dominated strategies, see, for example, Fudenberg and Tirole (1991).

[9]Indeed, a dominant strategy equilibrium entails constant reactions functions for each player!

[10]See Section 4.1 below.

a prisoner's dilemma in Case N whenever refraining from conducting any R&D at all would improve their pay-offs relative to the unique Nash equilibrium R&D levels.

We now show that the presence of R&D opportunities actually frames firms in a prisoner's dilemma situation under a significant region of parameter choices, which we characterize below.

$$\begin{aligned}\pi_1(x_N, x_N) &\geq \pi_1(0, x_N) && \text{by the Nash property}\\ &> \pi_1(0,0) && \text{by strictly positive externalities}\end{aligned}$$

A complete characterization of the scope for a prisoner's dilemma in R&D follows.

Proposition 1: The R&D game constitutes a prisoner's dilemma if and only if one of the following conditions holds:

$$2(2-\beta)(1+\beta)\frac{a}{c} < 9b\gamma < \frac{2(2-\beta)(1+\beta)^2}{3\beta} \equiv \gamma^{\mathrm{I}} \tag{4}$$

or

$$\gamma^{\mathrm{C}} \equiv 2(1+\beta)^2\left(2\frac{a}{c}-1\right) < 9b\gamma \leq 2(2-\beta)(1+\beta)\frac{a}{c} \tag{5}$$

Proof: Using $\pi(0,0) = (1/9b)(a - c)^2$ from standard Cournot theory and comparing it with each of the two lines defining $\pi_i(x_N,x_N)$ yields the desired result, upon two straightforward computations, one for the interior equilibrium and another for the boundary one. All details are left to the reader. ■

Here (4) and (5) pertain to a prisoner's dilemma for the interior and the boundary equilibrium R&D levels, respectively. The first condition in (4), which we will refer to *as the interior solution condition,* defines an area under a hyperbola-shaped curve in $(b\gamma,\beta)$ space, so that it holds for almost all values of γ when β is close to zero.

Figure 1 illustrates and summarizes Proposition 1 and the underlying assumptions. Some guidance as to how to read it follows.

(i) Points above (below) the 'Int.' curve are those for which the equilibrium R&D for Case N is interior (on the boundary).
(ii) The SOC curve bounds from below the area for which the SOC holds.
(iii) Points below γ^{I} (above γ^{C}) correspond to the case in which conducting no R&D leads to higher profits for firms than conducting the interior (boundary) Nash equilibrium level. In other words, overall, we have a prisoner's dilemma in the shaded area.

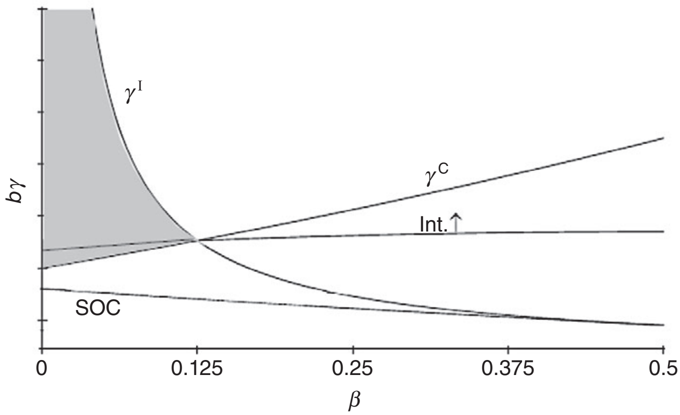

FIG. 1 Thresholds for $a = 6$ and $c = 2$

Some observations are in order. First, when spillovers are close to zero, the two firms would be better off agreeing not to conduct any R&D, almost independently of the R&D costs they would need to incur (see the shaded area in Fig. 1). Under moderate spillover levels, a prisoner's dilemma holds only when the cost of conducting R&D (i.e. γ) is relatively low, whereas firms will be better off conducting the Nash equilibrium levels of R&D when γ is high. The intuition for this result is quite easy to grasp: a higher cost of R&D directly deters firms from engaging in high levels of R&D, thus naturally dampening the scope of a prisoner's dilemma in R&D.

Considering both conditions in (4) and (5), it becomes evident that a no-R&D agreement works to the firms' advantage only for low levels of the spillover parameter, suggesting that the R&D prisoner's dilemma and the presence of significant levels of spillovers are mutually exclusive. This is reflected quite clearly in Fig. 1, which indicates that, for the chosen parameter values, a prisoner's dilemma does not hold when the spillover parameter exceeds 0.125, irrespective of the level of R&D costs. For the general case, it can easily be shown that the two inequalities in each of (4) and (5) are mutually consistent if and only if

$$\beta \leq \frac{c}{3a - c} \tag{6}$$

Hence, in view of Assumption 1 and (6), a prisoner's dilemma cannot possibly hold when the spillover parameter exceeds 0.20.

The incompatibilty between a prisoner's dilemma in R&D and spillover effects is quite intuitive since imperfect appropriability of R&D is broadly thought of as an impediment to private industrial R&D activity: the more difficulty firms face in being the sole exploiter of their know-how,[11] the less they will engage in privately financed R&D, due to the standard public-goods or commons problem. Thus the presence of spillovers mitigates the potential for a prisoner's dilemma in the R&D game, but tends to replace it with another familiar source of inefficiency in economic settings: free riding (on rival's R&D activity)! Indeed, it can easily be verified that each firm's equilibrium R&D level decreases with the level of spillovers (i.e. $\partial x_N/\partial\beta < 0$).[12] Furthermore, as shown in AJ, an R&D cartel conducts more R&D than the non-cooperative solution whenever spillovers are high (i.e. $\beta \geq 1/2$), which is a good reflection of the fact that an R&D cartel internalizes the spillover externality.

It is worth stressing that a prisoner's dilemma invariably holds under zero or sufficiently low spillovers, irrespective of the level of R&D costs. In particular, under zero spillovers, although x_N decreases to 0 as γ increases to ∞, a very large value of γ still leads to a very small equilibrium R&D level, which nevertheless indicates that firms are caught in a prisoner's dilemma.

From a theoretical standpoint, this result is extremely simple and rather intuitive. Yet, from a practical standpoint, it is likely to have significant implications, since in practice intra-industry spillover effects tend to be moderate in most industries.[13] In addition, it sheds quite some new light on firms' incentives for conducting process R&D in industries characterized by small spillover parameters: the key driving force behind privately financed R&D is a prisoner's dilemma mechanism! We shall return to this issue below to address it from the point of view of consumer and social welfare. We shall also argue that this result sheds new light on some well-known stylized facts in the economics of innovation.

This simple result has some related antecedents in the innovation literature. Brander and Spencer (1983) show that firms' equilibrium R&D levels in a general two-stage model with strategic commitment and no spillovers tend to be excessive in the sense that they reflect each firm's perception that raising R&D will provide a higher market share in the ensuing Cournot competition. In this influential work, these authors' use of the qualifier 'excessive' was against a benchmark of a one-stage model wherein firms would choose both process R&D and output levels simultaneously (in which case market share

[11]These difficulties might include a variety of factors in different industries, such as firms' inability to patent due to technological characteristics or patent policy choices, geographical proximity of rival firms, ease of innovation around existing patents or reverse engineering etc.

[12]This decline in firm R&D level is relatively slow, since effective R&D level, defined as the total R&D accruing to a firm at equilibrium or $X_N^{AJ} = (1+\beta)x_N^{AJ}$, is actually inverse U-shaped in β. More precisely, X_N^{AJ} increases in β on [0,1/2] but then decreases in β on [1/2,1].

[13]In addition, Amir (2000a) argues using a mix of formal and intuitive arguments that the AJ model has an in-built tendency to amplify spillovers across firms, and that the model faces significant validity issues when spillovers are high. To provide a flavor, note that Amir (2000a) demonstrates that spillovers higher than $\sqrt{2}-1$ in the duopoly case would violate a plausible postulate on spillover effects.

pre-emption ceases to be relevant). With respect to their finding, the present result may be thought of as a more elementary alternative to argue that R&D levels can be excessive from the firms' standpoint while using a meaningful and well-known benchmark derived from the same (two-stage) model: the prisoner's dilemma metaphor. In a two-stage model where binary R&D decisions emerge endogenously, with firms conducting either full or no R&D due to their having pay-offs that are convex in own R&D, Amir *et al*. (2010) show that a prisoner's dilemma of the standard variety (i.e. in the resulting 2×2 R&D game) emerges for a subset of parameters of the model (also see Amir, 2000b). Finally, Bachiegga *et al*. (2008) characterize a prisoner's dilemma in a modified version of the AJ model where firms decide in an added initial period whether they will engage in R&D or not. Unlike the present paper, their modification allows them to use the standard definition of a prisoner's dilemma.

3.2 Welfare Comparison

In this subsection, the focus is on the second-best social planner view of the comparison between the two-stage non-cooperative solution (Case N) and the no-R&D agreement. Adopting standard usage, the qualifier 'second-best' applied to the social planner's conduct stands for situations in which the planner is empowered to decide on the two firms' R&D levels but not on the firms' market conduct. It is then natural to postulate that the firms will continue to be Cournot competitors in the product market, as opposed to say perfect competitors (as would be the case under first-best planning).

In addition, second-best in the present setting also includes the stipulation that the planner's authority does not extend over the conduct of R&D, which thus continues to be carried out in two independently run laboratories characterized by the same level of natural spillovers, β (for more on this benchmark in an R&D oligopolistic setting, see Suzumura, 1992).

The usual Marshallian social welfare for the second-best benchmark is given by (for any R&D levels x_1 and x_2 by the two firms)

$$W(x_1,x_2)=\int_0^{q_1^*+q_2^*}(a-bt)\mathrm{d}t-(c-x_1-\beta x_2)q_1^*-(c-x_2-\beta x_1)q_2^*-\frac{1}{2}\gamma\left(x_1^2+x_2^2\right)$$

where

$$\begin{aligned} q_i^* &= [(a-2(c-x_i-\beta x_j)+(c-x_j-\beta x_i)]/3b \\ &= [a-c+(2-\beta)x_i-(1-2\beta)x_j]/3b \end{aligned}$$

is per-firm equilibrium Cournot output when firms 1 and 2 have unit costs ($c - x_1 - \beta x_2$) and ($c - x_2 - \beta x_1$), respectively.

Upon some computation, the social welfare level when firms choose the action pair (x_N,x_N) is given

$$W(x_N, x_N) = \begin{cases} \dfrac{4\gamma(a-c)^2\left[9b\gamma-(\beta-2)^2\right]}{[9b\gamma-2(2-\beta)(1+\beta)]^2} & \text{if } 9b\gamma > 2(2-\beta)(1+\beta)\dfrac{a}{c} \\ \dfrac{4a^2}{9b} - \dfrac{\gamma c^2}{(\beta+1)^2} & \text{if } 9b\gamma \leq 2(2-\beta)(1+\beta)\dfrac{a}{c} \end{cases} \tag{7}$$

We now compare equilibrium welfare with welfare under no R&D.[14]

Proposition 2: The Nash equilibrium R&D levels always lead to higher welfare than no R&D, or $W(x_N,x_N) > W(0,0)$.

Proof: From standard Cournot theory, we know that no R&D leads to social welfare being $W(0,0) = 4(a-c)^2/9b$. We separate the proof in two cases.

Case 1: (x_N, x_N) is interior. Then a simple computation shows that when (x_N,x_N) is interior, i.e. when $9b\gamma > 2(2-\beta)(1+\beta)(a/c)$, $W(x_N,x_N) < W(0,0)$ iff $9b\gamma > [4(2-\beta)(1+\beta)^2]/(5\beta+2)$. Since these two inequalities in $9b\gamma$ are not compatible, the desired result follows.

Case 2: $x_N = c/(1+\beta)$. Then $W(x_N,x_N) < W(0,0)$ iff $9b\gamma > 4(1+\beta)^2[2(a/c) - 1]$. But a boundary equilibrium requires $9b\gamma \leq 2(2-\beta)(1+\beta)(a/c)$, which is not compatible with the previous inequality. Hence, the desired result follows. ■

It follows that R&D enhances welfare independently of the value of the spillover parameter and of the cost of conducting R&D. Thus there is no prisoner's dilemma for society as a whole. Referring back to Fig. 1, and recalling that the shaded area corresponds to those parameter combinations in $(\beta,b\gamma)$ space for which firms find themselves caught in a prisoner's dilemma due to R&D opportunities, note that this area always works to the advantage of society. In other words, the resulting R&D, which is excessive from the perspective of the firms, improves consumer surplus by leading to a higher industry output. Furthermore, this positive effect on consumer surplus outweighs the negative effect on producer surplus, since overall social welfare improves.

While the result that the availability of R&D options can constitute bad news for competing firms is somewhat counter-intuitive, the fact that the resulting prisoner's dilemma driven R&D is advantageous to society as a whole is entirely in line with standard conventional wisdom on the overall cost and benefit effects of R&D (see, for example, Griliches, 1995). Indeed, it

[14]We do not consider the potentially important possibility of one and only one firm conducting R&D, which tends to favor social welfare. The reason is that overall industry production efficiency is enhanced with asymmetric firms because a larger share of the industry output is produced by the more efficient firm. This production efficiency gain also translates into higher industry profits, hence also higher social welfare (see Salant and Shaffer, 1999).

is often argued that this is a common justification for the appropriateness of R&D subsidies (see, for example, Spence, 1984 or Hinloopen, 2000a).[15]

What the simple results of this paper bring out is that the well-known gap between the private and social incentives for R&D at the single industry level would be substantially larger if the prisoner's dilemma mechanism were absent or if firms managed to collude their way out of it. In the AJ model, this partial bridging of the social and private incentives for R&D happens for low values of the spillover parameter only, but these values most likely cover a significant part of the actual range of spillover effects in many industries (see Amir, 2000a).

4 R&D Cartel vs. no-R&D Agreement

In this section, we explore the merits of a natural form of R&D collusive agreement among firms, which would simply stipulates that firms should refrain from conducting any R&D at all, as a way to extricate themselves from the prisoner's dilemma. We shall argue that firms may find such an agreement attractive in view of a combination of profit incentives and practical considerations, such as simplicity in overall implementation and ease of monitoring rival's compliance. We then contrast this new collusive agreement with the now classical R&D cartel, which has been thoroughly investigated in the literature on R&D joint ventures.

4.1 The R&D Cartel Solution and the R&D Prisoner's Dilemma

We begin with a brief summary of the well-known results in AJ and the related literature dealing with an R&D cartel, usually referred to as Case C.[16] Under this scenario, firms choose equal private cost reduction levels in a collusive way, while remaining competitors in the market place. The pay-off function of the R&D cartel is given by the firms' joint profit conditional on the subsequent Cournot equilibrium, net of total R&D costs, and is equal to

$$\sum_{i=1}^{2} \pi_i (x_i, x_j)|_{x_1=x_2=x} = \frac{2}{9b}[a - c + (1+\beta)x]^2 - \gamma x^2 \tag{8}$$

The feasible action set is $A \triangleq \{x : x \le c/(1+\beta)\}$. In stage 1, firms choose an element of A in order to maximize (8). By assumption here, we impose that firms select identical private cost reduction levels.[17] In line with the approach

[15]One way to formalize (at the level of an industry) this cost–benefit argument is to consider the first-best planning solution wherein the social planner can also force firm conduct to coincide with price-taking behavior in the second stage (see AJ).

[16]For more discussion and results on this case, also see Kamien *et al.* (1992) and Amir (2000a).

[17]This pay-off reflects a tacit assumption that the two firms are constrained to select equal R&D levels in the cartel solution. As shown by Salant and Shaffer (1998) and Tesoriere (2009), the global solution may well call for asymmetric R&D levels for the two firms. Following much of the literature, we ignore the latter possibility in this paper.

for Case N, and with much of the literature, we assume that $b\gamma > 2(1+\beta)^2/9$, in which case joint profit is strictly concave in $x \in A$. The solution for the R&D cartel problem at hand is given by

$$x_C = \begin{cases} \dfrac{2(a-c)(1+\beta)}{9b\gamma - 2(1+\beta)^2} & \text{if } b\gamma \geq \dfrac{a}{c}\dfrac{2(1+\beta)^2}{9} \\ \dfrac{c}{1+\beta} & \text{if } b\gamma < \dfrac{a}{c}\dfrac{2(1+\beta)^2}{9} \end{cases}$$

with associated equilibrium profit

$$\pi_i(x_C, x_C) = \begin{cases} \dfrac{\gamma(a-c)^2}{9b\gamma - 2(1+\beta)^2} & \text{if } 9b\gamma \geq 2(1+\beta)^2 \dfrac{a}{c} \\ \dfrac{a^2}{9b} - \dfrac{\gamma c^2}{2(1+\beta)^2} & \text{if } 9by < 2(1+\beta)^2 \dfrac{a}{c} \end{cases}$$

This profit level is then clearly the best outcome for the two firms, assuming that they are constrained (by antitrust regulation) to remain competitors in the product market and to conduct symmetric levels of R&D (e.g. because transfers are not permitted by antitrust regulation, or perhaps simply not feasible or practical from the standpoint of the firms themselves). In particular, the profit level $\pi_i(x_C,x_C)$ is clearly at least as high as $\pi_i(0,0)$, since (0,0) is one of the options available to the cartel when choosing (x_C,x_C). Therefore, when discussing the merits of the no-R&D cartel agreement, we focus exclusively on its attractiveness on practical grounds *vis-à-vis* the standard R&D cartel (i.e. Case C) and on possible Pareto improvement *vis-à-vis* the non-cooperative case.

As is typically the case with static collusive solutions, the R&D cartel equilibrium yields a Pareto optimal outcome that is not a self-enforcing outcome, in the sense of being immune to opportunistic unilateral deviations.[18] Indeed, fixing firm 2's R&D level (say) at x_C, firm 1 will find it profitable to deviate to its best response to x_C, which is $r_1(x_C)$ here.

An exception is the knife-edge case $\beta = 1/2$, for which the cartel solution is actually stable since it calls for implementing dominant strategies of the non-cooperative game. Indeed, we know that when $\beta = 1/2$, $x_C = x_N$ (see AJ), and that R&D levels are dominant strategies in Case N. The latter result follows from the fact that the reaction functions in R&D space are globally constant when $\beta = 1/2$. Hence, $r_i(x_C) = r_i(x_N) = x_N = x_C$.

We conclude this subsection with some remarks on how the level of spillovers affects the firms' incentive to form a standard R&D cartel. When $\beta = 1/2$, the firms have no incentive to engage in R&D cooperation since the

[18]More precisely, the notion of Pareto optimality used here includes the additional constraint of equal treatment of the two firms, or symmetry (see Salant and Shaffer, 1998).

Nash equilibrium in R&D levels is Pareto efficient, so that Cases N and C simply coincide (see AJ). A tedious but simple computation establishes that the incentive to cooperate for the firms (when equilibria are interior), as measured by the difference $\pi_i(x_C,x_C) - \pi_i(x_N,x_N)$, is maximal at $\beta = 1$. It is also very high at $\beta = 0$. Since this incentive is non-existent at $\beta = 1/2$, we conclude that it is overall essentially U-shaped in the level of spillovers. This result is somewhat counter-intuitive since it is generally thought that a higher spillover will make R&D more of a public good, which will induce more free-riding behavior on the part of the two firms, and make cooperation more desirable from their point of view. In other words, one might plausibly think that the incentive to cooperate ought to be increasing in β. While this common intuition holds for large spillovers, i.e. over the interval $\beta \in [1/2,1]$, it is essentially reversed for small spillovers, i.e. for $\beta \in [0,1/2]$.

Since, as reported in Amir (2000a), the AJ model is more likely to be fully valid as a model of strategic and cooperative R&D for a large class of industries and R&D processes when the spillover parameter is small, the aforementioned intuition reversal for $\beta \in [0,1/2]$ is somewhat unsettling. The results of Section 3 may be invoked to shed some light on this issue. Indeed, the fact that the two firms tend to be caught in a prisoner's dilemma when the spillover parameter is small (see Fig. 1) provides them with a powerful incentive to cooperate as a way of escaping the prisoner's dilemma trap. In this perspective, the extent to which R&D is a public good offers the primary explanation for why firms might prefer cooperation at high spillovers (in line with standard intuition), but a desire on the part of firms to escape the prisoner's dilemma trap plays the same role at low spillovers.

4.2 On no-R&D Agreements

Recall that in Case C, the two firms enter into an agreement that specifies that each of them selects its R&D level in order to internalize the R&D externality, but that the two firms continue to conduct R&D in separate labs characterized by the natural spillover level, β. In many cases, the firms may find it difficult, if not impossible, to monitor each other and ensure the rival's compliance with the cartel agreement.[19] This is exacerbated by the fact that any additional R&D beyond the agreed-upon level may plausibly be kept secret from one's cartel partner. Indeed, the partner may well find it difficult to infer from the level of natural spillovers received from the deviating firm that the latter is conducting more R&D than specified under the cartel agreement.[20]

[19]Some related issues are examined in d'Aspremont *et al.* (2000).

[20]It is worth noting that the cheated partner fares differently when β is below 1/2 than when β is above 1/2. In the first case, this partner is hurt by the deviation (since $\partial\pi_i/\partial x_j < 0$ when β is below 1/2), while in the second stage, the partner actually benefits from such a deviation (since $\partial\pi_i/\partial x_j > 0$ when β is below 1/2).

In the same vein, an R&D collusive agreement that calls for no R&D to be conducted by either firm will also generally fail to be stable or immune to opportunistic deviations. In other words, a firm will typically prefer to conduct a relatively high level of R&D if it knows its rival is committed to a policy of zero R&D, i.e. $r_1(0) > 0$. However, in contrast to the standard cartel situation, a no-R&D agreement will tend to be substantially easier to monitor by the participating firms in many situations. Monitoring a cartel member who is party to an agreement for not conducting any R&D at all may be quite a bit less demanding than monitoring a rival who is committed to a positive level of R&D but may covertly alter its R&D level to higher or lower levels than specified by the R&D cartel agreement.

In particular, if the cartel agreement is contemplated early on in the life of an industry, it may simply call for no lab to be built by either firm in the first place. Such a clear-cut commitment will often lend itself quite easily to monitoring by the other cartel member, a secret lab being a feature that is harder to conceal by a potential deviator. Furthermore, saving on the fixed costs of building a lab in the first place offers an additional incentive for engaging in a no-R&D agreement, relative to the case where the fixed cost of building a lab has already been sunk.

4.3 On Some Antitrust Considerations

In most countries, current antitrust legislation allows firms to enter into R&D cooperative agreements, provided they remain competitors on product markets. Recent theoretical work has tended to confirm the well-founded nature of this policy in terms of its implications on R&D propensity and welfare (see in particular Katz, 1986; AJ; Kamien *et al*., 1992).[21]

The simple results of this paper suggest that antitrust authorities should take notice of the fact that there is a potential on the part of firms to engage in R&D cooperation solely with a view to collude on jointly avoiding process R&D altogether. While one might argue that no-R&D collusion is simply a form of R&D cooperation among competitors in product markets, the intent of such permissive antitrust legislation was probably to allow competitors to pool resources and know-how dedicated to R&D with a view to increase total R&D relative to a regime of no cooperation in R&D. In other words, the intent behind allowing R&D cooperation was to allow firms to benefit from wider access to R&D, be able to afford more of it through cost sharing and avoid wasteful duplication. If instead, firms engage in R&D-curtailing agreements as a way to extricate themselves from the stranglehold of the prisoner's dilemma discussed here, then antitrust authorities should invoke standard anticollusion legislation to outlaw this potential behavior. The welfare results derived

[21]Some important qualifications are discussed by Martin (1996).

here provide a clear justification for invoking such legislation (both under a consumer surplus and under a social welfare standard).

One important policy implication of our simple results is that a permissive policy towards R&D cartels is more justified when the spillover effects are high. Indeed, under low spillovers, one key hitherto unrecognized aspect of R&D cartels is that they would allow firms a legal way out of a prisoner's dilemma that always benefits consumers as well as society as a whole.[22]

If one considers a potential no-R&D cartel as just another form of illegal cartel, then the issue of viability of such a cartel naturally arises and the theory of repeated games offers the most natural framework for analyzing such situations. Although players' propensity to reach and sustain agreements out of prisoner's dilemma situations is generally notoriously limited,[23] this may not quite apply in the present setting. Indeed, an R&D-curtailing agreement may be quite easy to monitor in many cases since it may involve an agreement not to build R&D facilities or not to have an R&D division. Such commitments are likely to be more difficult to defect on without detection by the rival.

5 Conclusion

Using a plausible definition of a prisoner's dilemma for games with a continuum of actions, this paper has argued that, for the standard model of R&D, in the version with output spillovers as proposed by AJ, firms end up facing a prisoner's dilemma in their R&D decisions whenever the spillover parameter is below a given threshold (bounded above by 20 per cent) and the cost of conducting R&D is not too high. This characterization is quite intuitive since both higher spillovers and higher R&D costs lead to a lower propensity for R&D, and thus tend to mitigate the prisoner's dilemma at hand. On the other hand, by forcing firms to engage in more R&D than they would collectively wish to, this prisoner's dilemma always works in favor of consumers and society as a whole, as one would expect.

This provides a new perspective on the incentives behind privately funded R&D. In particular, this prisoner's dilemma contributes to partly closing the well known gap between the social and the private incentives for R&D.

This simple result also offers a new perspective on the incentives that firms have for R&D cooperation in the form of an R&D cartel, which are the

[22]Some limitations of this view deserve mention here: fixed costs, risk-sharing and duplication costs in R&D are factors that would tend to go the other way, but are not included as part of the simple model under consideration.

[23]Indeed, a basic insight from game theory is that any finitely repeated prisoner's dilemma possesses only one Nash equilibrium, which consists of the perpetual repetition of the one-period dominant-strategy (inefficient) equilibrium, irrespective of the length of the horizon. Cooperation may emerge only with infinite repetition, and then only if the discount factor is sufficiently high (see, for example, Fudenberg and Tirole, 1991).

strongest at very high and very low spillovers, and the weakest at mid-level spillovers. These incentives are mostly guided by a desire to internalize the imperfect appropriability externality at high spillovers, as is commonly believed. However, under low spillovers, firms' incentives for R&D cooperation are instead driven by a desire to escape from the R&D prisoner's dilemma trap. One important consequence is that R&D cooperation in the form of a standard R&D cartel is not socially desirable in industries with low spillovers, and that a more discriminating policy might be called for.

This prisoner's dilemma directly implies that, when spillovers are small, relative to the non-cooperative mode of conducting R&D, firms will find it to their advantage to engage in an unusual sort of collusion: jointly refraining from engaging in R&D. While clearly dominated by a standard R&D cartel, this no-R&D agreement may be easier to implement. Some related antitrust considerations are discussed.

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