Knowledge spillovers spur cost reduction

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Abstract

This paper studies the effects of knowledge spillovers among product market competitors in different science-based industries. It argues that in industries in which outgoing spillovers decrease the effectiveness of a firm's R&D in reducing costs, the IP protection should be strengthened in order to protect the innovators from dissemination of knowledge. Low spillovers imply that rivals' R&D decisions are strategic substitutes. However, in industries in which outgoing spillovers increase the marginal productivity of a firm's R&D, the IP protection should be such that facilitates knowledge diffusion. We show that if spillovers are large enough so that firms' R&D decisions are strategic complements, both incoming *and* outgoing spillovers spur R&D in equilibrium. Cross-firm spillovers can foster innovation even in a homogeneous-product industry, under Bertrand and Cournot competition.

Keywords: R&D spillovers, feedback mechanism, process innovation, incentives to innovate

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1 Introduction

Innovation in knowledge-based industries and technological parks depends significantly on technological interactions among research units and the intensity of knowledge diffusion, which depends on the strength of intellectual property (IP) protection. Levin (1988) studies the effect of spillovers on R&D activity in high-technology industries and states that there are differences in technical advances in different industries. He argues that innovation "stands alone" and spillovers diminish the marginal productivity of a firm's innovation in material and drug industries prior to the revolution in genetic engineering. However, in pharmaceuticals and electronics-based industries, innovations are "building blocks" and spillovers increase the marginal productivity of a firm's R&D. Feldman (1999) also provides a survey of the empirical literature and argues that knowledge spillovers across diverse firms within a region contribute to higher rates of innovation and increased productivity. We study firms' incentives to innovate in industries in which the feedback mechanisms are different in "nature" and discuss the characteristics of the industries in which IP policies should facilitate knowledge diffusion rather than putting limitations.

We study the characteristics of the R&D process in precisely these industries in which feedback is reinforced. We argue that if firms' R&D decisions are strategic complements, larger outgoing spillovers foster innovative. In these industries, the IP protections should be weakened. If we allow for endogenous spillovers, firms would choose to disclose their knowledge to their product market competitors. In these industries, spillovers make a firm's own R&D more productive. A researcher finds it cheaper to solve her technological problem by accessing another researcher's R&D output, which is disclosed by patents or publications.[1] The other researcher can also build on this new innovation, facilitated by spillovers, and further improve her own results.[2] Using patent and citation data, Belenzon (2012) argues that an R&D-taking firm reabsorbs its spilled knowledge by recombining its own existing ideas with external follow-up developments in novel and unexpected ways. For example, Intel cites a Microsoft patent that is in turn cited by another Microsoft patent. In this case, Intel's follow-up development of Microsoft's original patent is internalized by Microsoft in its new invention. Similarly, we

[1] Spillovers are more likely to depend on R&D outputs than on R&D inputs, i.e., a researcher's effort. In a stochastic framework, a researcher benefits from another's research only if both succeed (inputs are irrelevant); i.e., innovative results need to be successfully produced by both researchers, allowing them to build thereon. Jaffe & Trajtenberg (2002) use patents and citations (R&D outputs) to infer patterns of knowledge diffusion.

[2] Spillovers are more intense within geographic areas and across firms with similar technologies and existing expertise (Feldman & Audretsch (1999)). They also depend on the strictness of IP law and the stage of the R&D and commercialization process.

consider a framework in which outside knowledge feeds into a firm's internal R&D.

Existing models with exogenous R&D spillovers, based on D'Aspremont & Jacquemin (1990) and Kamien, Muller & Zang (1992), assume that firms autonomously invest in R&D and there are no interactions during the R&D process. Spillovers have either no effect or negative effects on the marginal productivity of a firm's R&D. In equilibrium, they argue that larger outgoing spillovers decrease R&D. In these industires, Poyago-Theotoky (1999) shows that firms will never disclose any of their information when they compete in R&D.

We study cost-reducing R&D incentives in a two-period model in which firms first independently acquire R&D to improve their efficiency and, then, compete à la Cournot in the product market. The analysis focuses on the equilibrium R&D incentives when cross-firm spillovers are large, making rivals' R&D decisions strategic complements: an increase in R&D by one firm elicits increased R&D from the other.[3] The firms' objective is precisely to reduce the production cost; i.e., a firm's incentive to steal business is weak relative to its stronger incentive to improve its own efficiency. If the feedback is regenerative, by conducting more R&D, a firm contributes to another firm's R&D output through outgoing spillovers while indirectly improving its own R&D performance.[4] This occurs because incoming spillovers allow the innovative firm to internalize (at least) some share of the provided benefit. The return to cost reduction increases with outgoing spillovers, as do the gains from undertaking R&D. As outgoing spillovers intensify, a firm has stronger incentives to generate more R&D itself to produce more efficiently. Therefore, firms will profit more if the IP protection is weak, allowing for larger spillovers.

We perform this analysis by considering general demand and cost functions and specify the conditions under which outgoing spillovers foster R&D in equilibrium. We then consider a special case of a homogeneous-product industry with linear demand in which our results clearly hold. This analysis establishes that the relationship between outgoing spillovers and firms' equilibrium R&D depends on the nature of strategic interactions in the R&D stage: rivals' R&D decisions need to be strategic complements. However, we show that it does *not* depend

[3] For instance, Intel and Motorola compete in the market for semi-conductor chips and employ closely related technologies. Thus, large cross-spillovers occur, and their R&D decisions are strategic complements. Phillips and Segway, however, compete in the hard disk market but use different technologies, i.e., magnetic and holographic. These firms experience small spillovers, and their R&D decisions are strategic substitutes (Bloom, Schankerman & Van Reenen (2013)).

[4] When knowledge is more articulable, it is easily conveyed via journal articles, project reports, prototypes, and other tangible mediums. When knowledge is more tacit in nature, it is transmitted via face-to-face interactions and direct communication. Feldman & Lichtenberg (2000) construct several indicators of tacitness using data on publicly supported R&D projects in the European Union. Fershtman & Gandal (2011) study the spillovers that occur through the interaction between researchers who contribute to the development of different open source software.

on the mode of competition in the product market: as long as firms' R&D reaction curves are upward sloping, outgoing spillovers can stimulate R&D in both Cournot *and* Bertrand settings.

In D'Aspremont & Jacquemin (1990) (AJ model, hereafter), outgoing spillovers always induce rivals to conduct *less* R&D in equilibrium. Outgoing spillovers harm the innovative firm and decrease its optimal R&D, even when firms' R&D decisions are strategic complements. This is because innovation is costly, and the innovator cannot internalize (even indirectly) any of the provided benefit. Therefore, regardless of the nature of R&D strategic interactions, as outgoing spillovers increase, the innovative firm always acquires less R&D. In industries in which the feedback mechanisms are as in AJ model, the IP protection should be strengthened. Firms would prefer not to disclose any of their information.

This paper is related to the existing literature on R&D incentives that derives a positive relationship between spillovers and R&D. However, this literature considers different frameworks that involve differentiated products, vertical relations (Milliou (2004)), endogenous spillovers (Katsoulacos & Ulph (1998), Piga & Poyago-Theotoky (2005)), learning and absorptive capacity (Kamien & Zang (2000)), partial cartelization, winner-take-all racing games, complementarities in open source software (Henkel (2004)), or network externalities (Choi (1993)). More specifically, the recombination of knowledge in innovative industries has been discussed in the context of R&D networks (König, Battiston, Napoletano & Schweitzer (2012)). If two firms establish a link in an R&D network, their knowledge stocks become immediately accessible. We derive a positive relationship between spillovers and R&D in a non-cooperative equilibrium with homogeneous goods in which firms' absorptive capacity is given (exogenous) and asymmetric.[5]

We contribute to the branch of the literature on exogenous spillovers inspired by D'Aspremont & Jacquemin (1990) and Kamien, Muller & Zang (1992). Rockett (2012) provides an excellent summary.[6] The conventional wisdom in this literature is that larger symmetric symmetric spillovers discourage cost-reducing investments. In particular, in homogeneous product markets, spillovers inhibit the attainment of a competitive advantage, and the existence and severity

[5] Cohen & Levinthal (1989) assume that R&D increases the capacity of firms to absorb know-how, and thus the existence of larger spillovers may stimulate innovative activities.

[6] Cassiman & Veugelers (2006) consider firms' ability in external knowledge acquisition. Amir & Wooders (1999) analyze the effects of one-way spillovers. Milliou (2004) uses the AJ innovation process and shows that the impact of symmetric spillovers on R&D is positive for a (vertically) integrated firm and negative for a non-integrated firm. Milliou (2009) examines the conditions under which, as long as spillovers are not large, firms may decide to let their R&D knowledge flow to competitors. Chalioti (2015) studies the effect of spillovers on researchers' incentives under moral hazard. Amir, Halmenschlager & Knauff (2017) examine, in an imperfect competition setting, whether the cost paradox - i.e., that equilibrium profits raise with unit cost - precludes technological progress.

of the free-rider problem induce firms to reduce investment in R&D as spillovers increase. This result does not hold when feedback is regenerative. If firms' R&D decisions are strategic complements, spillovers stimulate R&D.

The literature on *asymmetric* (exogenous) spillovers uses the AJ innovation process and is focused on which firm will take the lead or follow in a sequential-move game (De Bondt & Henriques (1995), Amir, Amir & Jin (2000)). Milliou (2009) focuses on the choice of a receiver of spillovers also being a sender in a differentiated product duopoly. Steurs (1995) considers homogeneous-product duopolies and argues that intra-industry spillovers diminish R&D while inter-industry spillovers can encourage R&D. We show that if R&D decisions are strategic complements, a firm's own R&D can increase with both incoming *and* outgoing spillovers, even in the same industry. The existing works on cumulative innovation also assume that innovation is sequential (Bessen & Maskin (2009)).

The empirical literature (Feldman (1999), Levin (1988)) finds that the development of knowledge-driven industries and technological parks is accompanied by feedback mechanisms that exhibit increasing returns to spillovers.[7] The regenerative feedback mechanism can be used to capture such technological interactions. The analysis of R&D strategies and their market implications needs to identify the special economics of feedback mechanisms that encourage the firms initiating knowledge - which will be diffused - to invest more heavily in R&D and contribute to the "building-block" of innovation. In such industries, firms may also have incentives to engage in collusive-like behavior to internalize knowledge flows (Bernstein & Nadiri (1989), Bloom, Schankerman & Van Reenen (2013)).

This analysis highlights interesting policy implications of both models (AJ and RF) regarding the degree of intellectual property (IP) protection and antitrust laws. I outgoing spillovers are endogenous and thus firms can decide how much of their research results becomes publicly available, in the AJ model, firms will never disclose any of their information when they compete in R&D. Thus, in industries in which feedback mechanism is as in the AJ model, firms desire the IP protection to be strengthened in order to protect themselves against spillovers. Non-cooperative R&D investments will also yield higher welfare, compared to Research Joint Ventures (RJVs).[8] In the RF model, even under R&D competition, firms will seek to exchange

[7] There is general consensus that the rate of technical advance is key in determining an economy's rate of growth. Growth theories suggest that differences in growth rates may result from differences in the returns to knowledge spillovers. Levin & Reiss (1988) show that large spillovers and high R&D investment may coincide when the productivity of spillovers - i.e., the impact of spillovers on cost reduction - is also high.

[8] Scotchmer (2004) examines the strength of IP right protection in different countries and whether there are international mechanisms to repatriate the spillovers it generates.

their knowledge and IP protection needs to be weakened. In industries in which the feedback is regenerative, the policies regarding IP protection must be such that they facilitate communication and knowledge diffusion. A welfare improving policy will also motivate firms to form RJVs.

The rest of the paper is organized as follows. Section 2 describes the model and discusses the R&D production process. In section 3, we solve the rivalry game when we consider general demands and decompose the R&D incentives to analyze the effects of spillovers on equilibrium R&D. Section 4 compares the relationship between outgoing spillovers and equilibrium R&D in the RF model and that in the AJ model by assuming linear demand. We also highlight the policies implications of both models. Section 5 concludes.

2 The model

The market features two profit-seeking firms 1 and 2, indexed by i and j, where $i \neq j$. It is also populated by a continuum of identical consumers with mass equal to 1. The representative consumer's utility function is general of the form $U(q_i, q_j)$ which generates the inverse demand system $p_i = P_i(q_i, q_j)$, where p_i denotes firm i's price and q_i is its output. This function is downward sloping, $\frac{\partial P_i}{\partial q_i} < 0$, and the cross derivatives are negative, $\frac{\partial P_i}{\partial q_j} < 0$, implying that goods are substitutes. An increase in firm i's output has also a stronger impact on its own market price than on its rival's: $\left|\frac{\partial P_i}{\partial q_i}\right| > \left|\frac{\partial P_j}{\partial q_i}\right|$.

Firms initially have identical marginal cost $\overline{c}$ but take advantage of cost-reducing R&D opportunities in the presence of knowledge spillovers. Firm i's effective (final) marginal cost is $c_i = \overline{c} - y_i$, where y_i is the R&D output, which depends on its own R&D and to some extent on its rival's R&D; y_i is linear and separable in both x_i and x_j. Let β_i measures the degree of incoming spillovers - i.e., the fraction of firm j's R&D that is appropriated by firm i - and β_j denotes the degree of *outgoing* spillovers - i.e., the fraction of firm i's R&D that contributes to firm j's cost reduction.[9] The parameter β_i is exogenous and lies in $\left[0, \overline{\beta}_i\right]$, where $\overline{\beta}_i < 1$, for any $i = 1, 2$. Knowledge spillovers are value-creating, and their intensity depends on the characteristics of the technology used by each firm or the degree of tacit knowledge required in production. It is less than one, indicating the imperfect nature of spillovers: a firm's own R&D is (somewhat) more effective in its own cost reduction than in its rival's. Unless firms have created an RJV or agreed upon information sharing, spillovers are imperfect in any market with some degree

[9] Knott, Posen & Wu (2009) study the importance of spillover asymmetry in R&D activity.

of intellectual property protection. This is also the case whenever reverse engineering does not reveal all information regarding the underlying technology or, for instance, firms conceal some research results and delay publications.

We consider knowledge spillover mechanisms of different nature. In "stand alone" industries where there are no interactions between the firms during the innovation process, and the innovator cannot internalize any benefit from outgoing spillovers as in D'Aspremont & Jacquemin (1990) (AJ mechanism, hereafter), β_j does not affect the effectiveness of a firm's own R&D in enhancing efficiency, $\frac{\partial^2 y_i^A}{\partial x_i \partial \beta_j} = 0$. However, in industries where innovation is a "building block" and thus the feedback is regenerative (RF mechanism, hereafter), β_j increases the marginal productivity of x_i on reducing costs, $\frac{\partial^2 y_i}{\partial x_i \partial \beta_j} > 0$. Firm i's R&D output increases firm j's R&D performance due to outgoing spillovers. However, incoming spillovers allow the R&D-taking firm to absorb some share of a rival's research output that has already been developed using its own R&D results. Higher β_i and β_j make a firm's own R&D more productive, thereby allowing further cost reduction. For example, pharmaceuticals are created within a network of academic departments, testing labs, hospitals, and other organizations (Audretsch & Stephan (1996)). As more knowledge is created and diffused within this network, researchers are better able to advance their own R&D results. However, whether these technological interactions favor the equilibrium level of innovation will also depend on the nature of firms' strategic interactions in the product market.

To reach the R&D level x_i, firm i incurs the R&D cost $g_i(x_i)$, where $g_i(0) = 0$, $g_i'(0) = 0$ and $\lim_{x_i \to \infty} g'(x_i) = \infty$. This cost-of-R&D function is twice continuously differentiable and convex, implying that there are diminishing returns to scale in the R&D process. We can derive the equilibrium and examine the effects of spillovers on the optimal R&D incentives by considering general demand and cost functions. Thus, firm i's net profit for any realization of the marginal cost is $\Pi_i = (P_i - \bar{c} + y_i)q_i - g(x_i)$.

3 Feedback mechanism and R&D incentives

We derive the equilibrium R&D incentives of firms that, in period 1, invest simultaneously in cost-reducing innovation and, in period 2, engage in Cournot competition. We recursively solve the game and perform a comparative statics analysis to examine the effect of spillovers on R&D.

3.1 Equilibrium R&D investments

In period 2, firms compete in quantities and maximize their 'Cournot' profit $\pi_i = (P_i - c_i)q_i$. The following assumptions on the profit functions need to hold. Each firm's profit function is strictly quasi-concave in its own output, and the slopes of firms' reaction functions in the product market are less than one, $\frac{\partial^2 \pi_i}{\partial q_i^2} + \left| \frac{\partial^2 \pi_i}{\partial q_i \partial q_j} \right| < 0$ for any i, j. This inequality guarantees that in the production stage, there exists a unique interior Nash equilibrium in quantities. The cross derivative is negative, $\frac{\partial^2 \pi_i}{\partial q_i \partial q_j} < 0$, guaranteeing that firms' quantity decisions are strategic substitutes. Firms compete for consumers and their equilibrium quantities are $q_i(x_i, x_j)$ and $q_j(x_i, x_j)$. Lemma 1 highlights the effects of a firm's R&D on its own production and on its rival's.

Lemma 1 (Effects of R&D on optimal outputs) *Firm i's optimal output is increasing in*

(i) its own R&D, $\frac{\partial q_i}{\partial x_i} > 0$;

and *(ii) its rival's R&D,* $\frac{\partial q_i}{\partial x_j} > 0$, *if and only if,* $\frac{\partial^2 \pi_i}{\partial q_i^2} \frac{\partial c_i}{\partial x_j} > \frac{\partial^2 \pi_j}{\partial q_i \partial q_j} \frac{\partial c_i}{\partial x_i}$.

The functions of q_i *and* q_j *are linear and additively separable in* x_i *and* x_j, $\frac{\partial^2 q_i}{\partial x_i \partial x_j} = 0$.

Proof. In Appendix $(A.1)$. ■

We decompose the underlying effects of a firm's R&D on its own profits to interpret the rivals' strategic R&D motives: $\frac{\partial \Pi_i}{\partial x_i} = \frac{\partial \pi_i}{\partial q_j} \frac{\partial q_j}{\partial x_i} + \frac{\partial \pi_i}{\partial c_i} \frac{\partial c_i}{\partial x_i} - g_i'$. There is a direct effect on cost reduction, $\frac{\partial \pi_i}{\partial c_i} \frac{\partial c_i}{\partial x_i} = \frac{\partial c_i}{\partial x_i} q_i$, and an indirect effect due to product market competition that is captured by $\frac{\partial \pi_i}{\partial q_j} \frac{\partial q_j}{\partial x_i}$, where

$$\frac{\partial q_j}{\partial x_i} = \frac{1}{\Omega} \left(-\frac{\partial^2 \pi_j}{\partial q_i \partial q_j} \frac{\partial c_i}{\partial x_i} + \frac{\partial^2 \pi_i}{\partial q_i^2} \frac{\partial c_i}{\partial x_j} \right),$$

and $\Omega \equiv \frac{\partial^2 \pi_1}{\partial q_1^2} \frac{\partial^2 \pi_2}{\partial q_2^2} - \frac{\partial^2 \pi_1}{\partial q_2 \partial q_1} \frac{\partial^2 \pi_2}{\partial q_1 \partial q_2} > 0$ from the stability condition. The strategic interactions are twofold. On the one hand, the innovative firm benefits from conducting R&D itself because it will gain a cost advantage and extend its business at the expense of its rival's. On the other hand, the innovative firm is harmed because its own R&D also reduces its rival's initial marginal cost due to outgoing spillovers, strengthening its rival in the product market. However, when the latter effect dominates the former, a firm's R&D will induce its competitor to produce more, making the derivative $\frac{\partial q_j}{\partial x_i}$ positive.

We simultaneously solve both firms' maximization problem and derive the optimal values of x_i^R and x_j^R, where the superscript R denotes the equilibrium incentives in the RF model. In equilibrium, the level of R&D conducted by the firms depends on the strategic properties of agents' R&D incentives. Thus, we need to specify the conditions under which incentives are strategic substitutes or complements.

Following Chalioti & Serfes (2017), the nature of rivals' strategic interactions depends on the sign of the derivative $\frac{dx_i}{dx_j} = -\frac{H_i}{\Delta}$, where

$$H_i \equiv \underbrace{\frac{\partial^2 \pi_i}{\partial q_j^2}}_{>0 \text{ or } <0} \underbrace{\frac{\partial q_j}{\partial x_j}\frac{\partial q_j}{\partial x_i}}_{>0} + \underbrace{\left(-\frac{\partial^2 \pi_i}{\partial q_i^2}\right)}_{>0} \underbrace{\frac{\partial q_i}{\partial x_i}}_{>0}, \tag{1}$$

and $\Delta < 0$ by the second order conditions. The sign of the first term in (1) depends on the second derivative of q_j on the price of good i. In particular, we consider that firms' products exhibit decreasing (increasing) substitutability, if an increase in a rival's production diminishes a firm's profit at a decreasing (increasing) rate: $\frac{\partial^2 \pi_i}{\partial q_j^2} > (<)\, 0$. For decreasing substitutability, the demand function of firm i in its rival's output needs to be convex, $\frac{\partial^2 P_i}{\partial q_j^2} > 0$. As q_j increases, the two products become weaker substitutes; i.e., the negative effect of q_j on the price of good i becomes smaller. Thus, if $\frac{\partial q_j}{\partial x_i} > 0$, decreasing substitutability is a source of strategic complementarity. For increasing substitutability, firm i's demand needs to be a concave function of q_j, $\frac{\partial^2 P_i}{\partial q_j^2} < 0$. The benefit of a higher x_i for firm i is smaller the higher the x_j (and hence the higher the q_j). This is a source of strategic substitutability.

To shed lights on the second term, we differentiate firm i's first-order conditions in the second stage of the game with respect to x_i which gives $-\frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i} = \frac{\partial^2 \pi_i}{\partial q_j \partial q_i}\frac{\partial q_j}{\partial x_i} + \frac{\partial^2 \pi_i}{\partial c_i \partial q_i}\frac{\partial c_i}{\partial x_i}$. On the one hand, a higher x_j (and thus a higher q_j) induces firm i to lower its own x_i because firm i's best-response in the product market to an increase in q_j is to become less aggressive by lowering its own q_i. Thus, investing less in R&D is firm i's profit-maximizing response to an increasing x_j. On the other hand, provided that $\frac{\partial q_i}{\partial x_j} > 0$, for a higher x_j, q_i increases and so does the benefit from a cost reduction. The effect on costs always dominates, implying that the second term in (1) is always positive.

Lemma 2 (Strategic interactions in R&D) *Provided that* $\frac{\partial q_i}{\partial x_j} > 0$ *and* $\frac{\partial q_j}{\partial x_i} > 0$, *firms' R&D decisions are strategic complements when demand functions exhibit decreasing or weakly increasing substitutability between firms' products:* $\frac{dx_i}{dx_j} > 0$ *if and only if*

$$\frac{\partial^2 \pi_i}{\partial q_j^2} > \frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i}\frac{\partial q_i}{\partial x_j}\left(\frac{\partial q_j}{\partial x_j}\frac{\partial q_j}{\partial x_i}\right)^{-1}.$$

Proof. In Appendix ($A.2$). ■

We can show that as long as the condition in Lemma 2 holds so that firms' R&D decisions are strategic complements, outgoing spillovers can foster innovation in equilibrium.

3.2 Effects of spillovers on equilibrium R&D

We show that in the RF model, if the IP protection is weak so that the innovator's *R&D reaction curve is upward sloping*, larger outgoing spillovers boost a firm's R&D. This result counters the prediction of the existing literature based on D'Aspremont & Jacquemin (1990) that outgoing spillovers always diminish optimal R&D. We show that such motives are reversed when the feedback is reinforced.

We totally differentiate firm i's first-order condition with respect to β_j and get

$$T_i + \delta_i \frac{dx_i^R}{d\beta_j} + H_i \frac{dx_j^R}{d\beta_j} = 0, \tag{2}$$

where

$$T_i \equiv \frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 q_j}{\partial x_i \partial \beta_j} + \frac{\partial \pi_i}{\partial c_i}\frac{\partial^2 c_i}{\partial x_i \partial \beta_j} + \frac{\partial^2 \pi_i}{\partial q_j \partial \beta_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial^2 \pi_i}{\partial c_i \partial \beta_j}\frac{\partial c_i}{\partial x_i}. \tag{3}$$

Equation (2) shows the effects of outgoing spillovers. We begin the analysis by considering the case in which cross-firm spillovers are large enough so that R&D decisions are strategic complements; i.e., $H_i > 0$, implying that $\frac{dx_i}{dx_j} > 0$ (see Lemma 2). An increase in a firm's R&D elicits increased R&D from the other. Firms' main objective is precisely to reduce the production cost: a firm's incentive to extend its market share is weak vis-à-vis its (stronger) incentive to enhance its efficiency. To achieve this objective, firms can exploit the cumulative nature of the RF mechanism.

The first two terms in (2) can be positive because $\frac{\partial^2 c_i}{\partial x_i \partial \beta_j}$ is negative; i.e., $\frac{\partial^2 q_j}{\partial x_i \partial \beta_j} = \frac{\partial q_j}{\partial c_i}\frac{\partial^2 c_i}{\partial x_i \partial \beta_j} + \frac{\partial q_j}{\partial c_j}\frac{\partial^2 c_j}{\partial x_i \partial \beta_j}$, where $\frac{\partial q_j}{\partial c_i} > 0$ and $\frac{\partial q_j}{\partial c_j} < 0$. In the AJ model, the marginal return of a firm's R&D in its own cost reduction remains unchanged with outgoing spillovers, $\frac{\partial^2 c_i}{\partial x_i \partial \beta_j} = 0$, justifying why the sum of these two terms in that model is always negative. The third and fourth terms in (2) are equal to $\left(\frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} - \frac{\partial c_i}{\partial x_i}\right)\frac{\partial q_i}{\partial \beta_j}$. From the first order condition of firm i's maximization problem in the R&D stage, we get $\frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} - \frac{\partial c_i}{\partial x_i} = \frac{1}{q_i} g'(x_i) > 0$. Given also that $\frac{\partial q_i}{\partial \beta_j} = \frac{\partial q_i}{\partial c_i}\frac{\partial c_i}{\partial \beta_j} + \frac{\partial q_i}{\partial c_j}\frac{\partial c_j}{\partial \beta_j}$, the positive term $\frac{\partial q_i}{\partial c_i}\frac{\partial c_i}{\partial \beta_j}$ can make both terms also positive. In the AJ model, the derivative $\frac{\partial q_i}{\partial \beta_j}$ is always negative because $\frac{\partial c_i}{\partial \beta_j} = 0$. The decomposition of the effects of β_j on firm j's incentives gives that all corresponding effects of incoming spillovers on a firm's own R&D are also positive (see Appendix A.3).

Proposition 1 (Effects of outgoing spillovers with general demand in RF model) *Assume that the IP protection is weak allowing for large cross-firm spillovers so that firms' R&D decisions are strategic complements,* $H_i > 0$ *and* $H_j > 0$*. If the feedback mechanism is such that* $T_i > 0$*, larger outgoing spillovers increase a firm's equilibrium R&D,* $\frac{dx_i^R}{d\beta_j} > 0$*.*

Proof. In Appendix $(A.3)$. ■

Proposition 1 shows the conditions under which our main result holds with general demand and cost functions. It requires the effects of outgoing spillovers on a firm's cost enhancement to be more important compared to the strategic benefits of R&D in terms of market share and the marginal productivity of a firm's R&D to increase with outgoing spillovers.

4 Linear demand for homogeneous goods

We will illustrate our results in a linear demand setting with homogeneous goods, considering also a feedback mechanism that satisfies the characteristics described in Section 2. Following Singh & Vives (1984), we assume that the representative consumer's utility is $U(q_i, q_j) = a(q_i + q_j) - \left[\frac{1}{2}\left(q_i^2 + q_j^2\right) + q_i q_j\right]$, implying that firms act as homogenous-product duopolists, facing demand $p = a - q_i - q_j$, where p denotes the price and a stands for the maximum willingness to pay, $a > \overline{c} > 0$.[10,11]

4.1 Regenerative feedback mechanism

Suppose that firm i's output y_i depends on its own R&D input, x_i, and to some extent on the rival's R&D output:

$$y_i = x_i + \beta_i y_j, \forall i, j. \tag{4}$$

[10]The utility function is separable and linear in the numeraire good. Provided that there are no income effects, we can perform partial equilibrium analysis.

[11]Instead of cost-reducing (process) innovation, one could consider a quality improvement in existing products. Product innovation can be captured by an increase in consumers' willingness to pay, measured by the parameter a. The profit functions are the same as in our analysis, implying that the equilibrium R&D decisions and comparative statics hold in both settings (Vives (2008)).

Substituting $y_j = x_j + \beta_j y_i$ into equation (4) implies

$$y_i = \frac{x_i + \beta_i x_j}{1 - \beta_i \beta_j}. \tag{5}$$

Thus, the feasibility bound that guarantees positive post-innovation marginal costs take the form $\overline{x_i}(x_j) = \left(1 - \beta_i \beta_j\right) \overline{c} - \beta_i x_j$ for any i and j. Firm i will commit to an R&D level $x_i \in \Omega$, where $\Omega \equiv \left[0, \left(1 - \beta_i \beta_j\right) \overline{c}\right]$.

This regenerative feedback mechanism indicates that firm i's R&D output increases firm j's R&D performance due to outgoing spillovers. However, incoming spillovers allow the R&D-taking firm to absorb some share of a rival's research output that has already been developed using its own R&D results. Higher β_i and β_j make a firm's own R&D more productive, thereby allowing further cost reduction. Hence, the RF mechanism displays increasing returns to spillovers and attempts to capture, in a static context, the reduced-form dynamics of the R&D process in high-technology industries where feedback is reinforced.

In period 2, firm i's 'Cournot' profit is $\pi_i = (a - q_i - q_j - c_i)\, q_i$, where $q^i : \Omega^2 \to R_+$. In equilibrium, firm i produces the output, $q_i = \frac{1}{3}(a - 2c_i + c_j)$, and receives the profit $\pi_i = (q_i)^2$. In period 1, before competition in the product market occurs, each firm i chooses the R&D level that maximizes $\Pi_i = q_i^2 - g_i(x_i)$. Thus, by equations (4) and (5), the output becomes

$$q_i = \frac{1}{3}\left(a - \overline{c} + \gamma_i x_i + \frac{2\beta_i - 1}{1 - \beta_i \beta_j} x_j\right), \tag{6}$$

where $\gamma_i \equiv \frac{2-\beta_j}{1-\beta_i\beta_j}$. The slope of firm i's R&D reaction curves depend on the sign of $\frac{\partial^2 \pi_i}{\partial x_i \partial x_j} = \frac{2\gamma_i(2\beta_i - 1)}{9\left(1-\beta_i\beta_j\right)}$. If the incoming spillovers are weak enough that $\beta_i < \frac{1}{2}$, firm i's R&D reaction curve is downward sloping and its R&D decision is a strategic substitute. Instead, if $\beta_i > \frac{1}{2}$, its R&D decision is a strategic complement, while if cross-firm spillovers are equal to $\frac{1}{2}$, each firm has a dominant strategy on R&D. The following assumptions on π_i also hold:[12]

$(R.1)$ $\frac{2\left(2-\beta_j\right)}{9\left(1-\beta_i\beta_j\right)^2}\left[2 - \beta_j + |1 - 2\beta_i|\right] < g''$

$(R.2)$ $\Delta \equiv \delta_i \delta_j - \frac{4\gamma_i\gamma_j(2\beta_i - 1)\left(2\beta_j - 1\right)}{81\left(1-\beta_i\beta_j\right)^2} > 0,$

where $\delta_i \equiv \frac{2}{9}\gamma_i^2 - g_i'' < 0, \forall i, j$. Assumption $(R.1)$ requires a strong form of convexity of the cost-of-R&D functions to guarantee that the slopes of the R&D reaction curves are between

[12] We also assume that the market parameter a is high enough relative to $\overline{c}$ such that both firms have incentives to conduct some R&D, guaranteeing that the equilibrium in R&D is interior (Amir, Amir & Jin (2000)).

-1 and 1. Assumption $(R.2)$ insures that the second-order conditions hold.[13] The equilibrium in R&D is unique and lies in the interior of the effective joint action space (x_i, x_j), where $x_i, x_j \in \Omega$. Solving the first-order conditions of the maximization problems of both firms, we obtain the levels x_i^R and x_j^R. We can perform a comparative statics analysis without using an explicit form for their levels.

4.2 RF and AJ models with linear demands

In the RF model, the decomposition of firm i's optimal R&D incentives with respect to β_j gives[14]

$$\frac{2\left(2\beta_i - 1\right)}{9\left(1-\beta_i\beta_j\right)^2}\left[\underbrace{3q_i^R}_{\text{output effect}} + \underbrace{\gamma_i x_i^R}_{\text{own-R\&D effect}} + \underbrace{\gamma_i \beta_i x_j^R}_{\text{rival-R\&D effect}} + \left(2-\beta_j\right)\frac{dx_j^R}{d\beta_j}\right] + \delta_i \frac{dx_i^R}{d\beta_j} = 0. \quad (7)$$

Equation (7) show the effects of outgoing spillovers in a homogeneous-produce duopoly with linear demand. *Outgoing* spillovers give rise to three *positive* effects. First, there is the *output* effect: if incoming spillovers exceed $\frac{1}{2}$, outgoing spillovers increase the marginal contribution of x_i to firm i's production output. The first two terms in (3) exactly capture the output effect. Note that with linear demand, $\frac{\partial \pi_i}{\partial q_j} = \frac{\partial \pi_i}{\partial c_i} = -q_i^R$, and in the RF model, $\frac{\partial^2 q_j}{\partial x_i \partial \beta_j} + \frac{\partial^2 c_i}{\partial x_i \partial \beta_j} = \frac{2-\beta_i}{3\left(1-\beta_i\beta_j\right)^2} - \frac{\beta_i}{\left(1-\beta_i\beta_j\right)^2} = -\frac{2(2\beta_i - 1)}{3\left(1-\beta_i\beta_j\right)^2} < 0$ for $\beta_i > \frac{1}{2}$. Thus, if firms' R&D decisions are strategic complements, the output effect is positive. Second, there is the *own-R&D* effect: when $\beta_i > \frac{1}{2}$, as outgoing spillovers increase, a firm's R&D becomes more effective in cost reduction, as the firm can now internalize the rival's improved research outcomes through incoming spillovers. Thus, a firm benefits by conducting more R&D itself. Third, there is the *rival* effect which arises only in the presence of the RF mechanism: when $\beta_i > \frac{1}{2}$, for larger outgoing spillovers, firm j's R&D now becomes increasingly more significant in firm i's production and equilibrium profits. Thus, as long as the incoming spillovers are also large, we argue that in industries

[13] The Hessian matrices are negative definite. These assumptions also determine the values of $\overline{\beta}_i$ and $\overline{\beta}_j$. For instance, assumption $(R.1)$ indicates that if $g_i(x_i) = \frac{k}{2}x_i^2$, $k = 10$ and $\beta_i = 0.85$, the spillover rate β_j needs to be less than 0.9.

[14] The decomposition of firm j's optimal R&D incentives with respect to β_j gives $\frac{2\gamma_j}{9\left(1-\beta_i\beta_j\right)}\left[3\beta_i q_j^R + \gamma_j\left(\beta_i x_j^R + x_i^R\right) + \left(2\beta_j - 1\right)\frac{dx_i^R}{d\beta_j}\right] + \delta_j \frac{dx_j^R}{d\beta_j} = 0$. Using also (7), we obtain $\frac{dx_i^R}{d\beta_j} = \frac{2(2\beta_i - 1)\Psi_j}{9\Delta\left(1-\beta_i\beta_j\right)^2}$, where $\Psi_j \equiv \frac{2\gamma_i\gamma_j}{9}\left[3\beta_i q_j^R + \gamma_j\left(x_i^R + \beta_i x_j^R\right)\right] - \delta_j\left[3q_i^R + \gamma_i\left(x_i^R + \beta_i x_j^R\right)\right]$. Assumptions $(R.1)$ and $(R.2)$ guarantee that $\delta_j < 0$ and $\Delta > 0$. Hence, we have $\Psi_j > 0$, implying $\frac{dx_i^R}{d\beta_j} > 0$ if and only if $\beta_i > \frac{1}{2}$ for all β_i and β_j.

in which the feedback is regenerative, the more knowledge a firm is able to appropriate from another firm's research or even initiate, the more R&D this firm acquires itself. The sum of the third and fourth terms in (3) capture the own-R&D and rival-R&D effects. In the RF model with linear demand, we have $\frac{\partial^2 \pi_i}{\partial q_j \partial \beta_j} = \frac{\partial^2 \pi_i}{\partial c_i \partial \beta_j} = -\frac{(2\beta_i - 1)(x_i + \beta_i x_j)}{3\left(1-\beta_i\beta_j\right)^2}$ and $\frac{\partial c_i}{\partial x_i} + \frac{\partial q_j}{\partial x_i} = -\frac{2\left(2-\beta_j\right)}{3\left(1-\beta_i\beta_j\right)}$. If $\beta_i > \frac{1}{2}$, larger outgoing spillovers increase the marginal productivity of both x_i *and* x_j, as well as firm i's benefits of doing more R&D itself. In D'Aspremont & Jacquemin (1990), the rival-R&D effect vanishes, and the output and own-R&D effects are negative for any level of β_i and β_j.

Corollary 1 (R&D incentives & Linear demand with homogeneous goods) *Under assumptions* (*R*.1) *and* (*R*.2)*, in the RF model, outgoing spillovers increase firm i's optimal R&D,* $\frac{dx_i^R}{d\beta_j} > 0$*, if and only if* $\beta_i > \frac{1}{2}$ *for all* β_i *and* β_j*, implying that the IP protection needs to be weak to allow for large cross-firm spillovers.*

In the AJ model, the innovator cannot internalize any benefit from outgoing spillovers. Firm i's effective output is

$$y_i = x_i + \beta_i x_j.$$

The counterpart of equation (7) is

$$\underbrace{-\frac{2}{3}q_i^A}_{\text{output effect}} + \frac{2}{9}\left(2-\beta_j\right)\left[\underbrace{-x_i^A}_{\text{own-R\&D effect}} + (2\beta_i - 1)\frac{dx_j^A}{d\beta_j}\right] + \theta_i \frac{dx_i^A}{d\beta_j} = 0, \tag{8}$$

where $\theta_i \equiv \frac{2}{9}\left(2-\beta_j\right)^2 - g_i'' < 0$ and $q_i^A = \frac{3}{2\left(2-\beta_j\right)} g_i'$. The superscript A denotes the values in the AJ model.[15]

Only the output and own-R&D effects arise and both are negative. The benefits of an increase in β_j are appropriated only by firm j. Outgoing spillovers only harm the R&D-taking firm. Thus, in equilibrium, the innovator undertakes less R&D to diminish its rival's gains from knowledge diffusion. In the AJ model, outgoing spillovers always diminish firm i's optimal

[15] Decomposing firm j's R&D with respect to β_j gives $\frac{2}{9}\left(2-\beta_j\right)\left[\, 2x_i^A + \left(2\beta_j - 1\right)\frac{dx_i^A}{d\beta_j}\right] + \theta_j \frac{dx_j^A}{d\beta_j} = 0$. Using (8) and substituting q_i^A and θ_i implies $\frac{dx_i^A}{d\beta_j} = -\frac{2}{9\Gamma_A}\left(2-\beta_j\right)x_i^A\left[\theta_j\left(1 + \frac{9k}{2\left(2-\beta_j\right)^2}\right) + \frac{4}{9}\left(2-\beta_i\right)\left(1-2\beta_i\right)\right]$, where $\Gamma_A \equiv \theta_i\theta_j - \frac{4}{81}\left(2-\beta_i\right)\left(2-\beta_j\right)\left(2\beta_i - 1\right)\left(2\beta_j - 1\right) > 0$. Given that $\theta_j < 0$, note that even if $\beta_i > \frac{1}{2}$, the amount in the bracket is positive, implying that $\frac{dx_j^A}{d\beta_i} < 0$ for any β_i and β_j.

R&D, regardless of the nature of R&D strategic interactions, $\frac{dx_i^A}{d\beta_j} < 0$ for any β_i and β_j.[16]

Figure 1. Effects of outgoing spillovers on optimal R&D

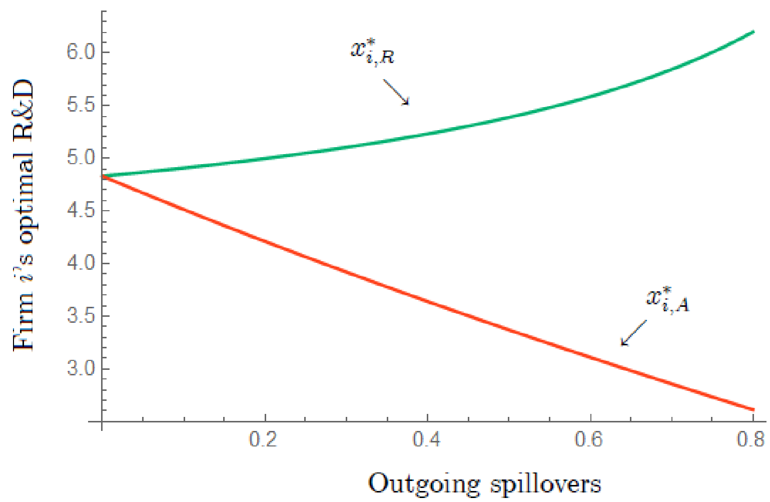

Figure 1 shows how firm i's optimal R&D changes with outgoing spillovers, β_j, in the RF and AJ model when $\beta_i = 0.6$. We also assume $a = 100$, $\bar{c} = 45$, and $k = 4$.

In the case in which firms' R&D decisions are strategic substitutes - where β_i and β_j are below $\frac{1}{2}$ - the relationship between outgoing spillovers and optimal R&D is negative in both models. An increase in a firm's R&D now dampens the R&D investment of the other firm. Larger outgoing spillovers make any attempt of the innovative firm to secure a cost advantage and strengthen its strategic position less effective, resulting in a decrease in its own equilibrium R&D.

Incoming spillovers also spur a firm's own R&D in equilibrium. This result is straightforward when R&D decisions are strategic complements. However, this happens even when they are strategic substitutes, but the intuition is different. In the RF model, a firm now innovates in order to take away business from its rival. However, it becomes more difficult for firm i to steal market share when a rival can readily "catch up" due to knowledge flows. Thus, firms

[16] Kamien, Muller & Zang (1992) consider spillovers of R&D expenditures: each firm observes the other firm's research input at the beginning of the R&D process rather than after. Thus, firm i's marginal cost is $c_i = \bar{c} - f_i(X_i)$, where $X_i = x_i + \beta_i x_j$, and f_i is a concave R&D production function; $f_i(0) = 0$, $f_i(X_i) \leq \bar{c}$, $f_i' > 0$ and $f_i'' < 0$ for all $X_i \geq 0$. As in the AJ model, the output and own-R&D effects surface and both are negative. Firms decide the level of their R&D expenditures, and then spillovers occur, implying that the knowledge diffused by a firm can only harm the R&D-taking firm. Thus, larger outgoing spillovers discourage firms from innovating.

enter into a prisoners' dilemma type of game. To secure a cost advantage, firms' eagerness to innovate increases with incoming spillovers.

4.3 Bertrand competition and optimal R&D

Outgoing spillovers can stimulate R&D in the RF model even if firms are involved in Bertrand competition. The main difference in firms' interactions in the Bertrand and Cournot settings is that for Bertrand rivals, product market competition gives rise only to detrimental effects on the innovator's profit. This is because cost-reducing innovation allows the R&D-taking firm to set a lower price. Competing for market share, a rival responds by also reducing its price, leading to lower profits for the innovator. Thus, due to the price war in the product market, outgoing spillovers that strategically strengthen a rival actually harm the R&D-taking firm.

If the feedback is regenerative, Proposition 2 states that a positive relationship between outgoing spillovers and optimal R&D can also hold for Bertrand rivals. To derive the optimal R&D incentives and analyze the effects of spillovers, we employ a demand system obtained by inverting the inverse demands as in Singh & Vives (1984), and Vives (1984). The superscript B indicates the equilibrium R&D decisions when firms compete à la Bertrand in the RF model.

Proposition 2 (Regenerative feedback and R&D of Bertrand rivals) *In the RF model with Bertrand competition, firm i's optimal R&D increases with outgoing spillovers,* $\frac{dx_i^B}{d\beta_j} > 0$, *if and only if its R&D reaction curve is upward sloping.*

Proof. In Appendix $(A.4)$. ■

When β_i and β_j are high enough so that their positive effects on efficiency improvement are more important than their negative effects on the innovator's strategic position, a positive relationship between x_i^B and β_j can be realized in both Bertrand and Cournot settings: it does not depend on the mode of competition in the product market. However, in the R&D stage, the innovator's R&D decisions need to be strategic complements.

All results that hold in a homogeneous-product duopoly also apply in markets with differentiated goods. For a given degree of product differentiation, as in the AJ model, the firms always invest more in R&D if the product market involves Cournot competition than if it involves Bertrand competition. We infer that the RF mechanism is stronger under Cournot than under Bertrand competition. In the Cournot case, by performing more R&D and thereby lowering its cost, the firm is tougher in the market and thus discourages its rival's sales, which in turn benefits itself. In contrast, in the Bertrand case, the firm's R&D lowers its cost and induces its rival to reduce prices, which in turn harms itself. Thus, Cournot competitors can better exploit the RF mechanism, for efficiency-enhancing and strategic reasons.

4.4 Welfare and IP policies

Important insights about the RF and AJ feedback mechanisms are drawn by performing a welfare analysis. We aim to infer whether research joint ventures (RJV) or non-cooperative R&D investments yield more welfare, while firms involve in Cournot competition in the product market. RJVs internalize the knowledge externality and eliminate the duplication of costs of conducting R&D. The RJV decides the levels of R&D, x_i and x_j, which maximize the joint profit

$$\pi^{RJV} = q_i^2 - g(x_i) + q_j^2 - g(x_j), \tag{9}$$

where q_i and q_j are given by equation (6).

For large outgoing spillovers so that firms' R&D decisions are strategic complements, each RJV member enjoys higher marginal returns to R&D than R&D competitors. This happens because in addition to the effects of R&D investments on an R&D competitive firm's profits, an RJV member also considers the *cross-profit* effect: firm i's R&D also affects firm j's profits, $\frac{\partial \pi_j}{\partial x_i} = \frac{2(2\beta_i - 1)}{3(1-\beta_i\beta_j)} q_j$.[17] If $\beta_i > \frac{1}{2}$, the cross-profit effect is positive, implying that the increase in profits resulting from an additional reduction in marginal costs exceeds the loss of profits resulting from a decline in the market share of a 'higher-cost' rival. R&D duopolists ignore this effect and thus invest less in R&D. If $\beta_i < \frac{1}{2}$, the opposite holds. RJV members enjoy higher profits and have incentives to collude. Note also that RJV firms innovate more in the RF model than in AJ model. Each firm can take advantage of the cumulative nature of the RF mechanism and innovate more itself, because it can now internalize the benefits of its own R&D that is spilled over to another RJV member.

Social welfare is the unweighted sum of both firms' profits and the consumer surplus $U(q_i, q_j) - p_i q_i - p_j q_j$, implying the function $U(q_i, q_j) - c_i q_i - c_j q_j - g(x_i) - g(x_j)$. Here, we count the own-action effects on net profits, the cross-profit effect as well as the increase in the consumer surplus. The social gains from the R&D activity are twofold. R&D reduces the inefficiencies in production, allowing firms to produce at a more efficient scale. The consumer-

[17] The 'cross-profits' effect is identical to the 'combined-profits' effect in Kamien et al. (1992).

surplus also increases: cost-reducing R&D allows a firm to produce more output and sell it a lower price. Thus, for any β_i and β_j, the welfare maximizing R&D levels acquired by both firms exceed the equilibrium RJVs and non-cooperative R&D levels.

This welfare analysis indicates that the organizational form of the firms in the R&D stage that leads to more innovation will be socially desirable. In turn, both models (AJ and RF) outline and suggest interesting market implications regarding the degree of intellectual property (IP) protection or antitrust laws. In industries in which innovation is a "building block", as in the RF model, the IP protections must be such that they facilitate communication and knowledge diffusion, making firms' R&D decisions strategic complements. A welfare improving policy will be firms to be motivated to form RJVs. Alternatively, in industries in which innovation "stands alone" as in the AJ model, firms desire strengthened IP protections to protect themselves against spillovers, implying that their R&D decisions are strategic substitutes. In this case, non-cooperative R&D investments will yield more welfare, compared to RJVs.

The statement that disclosure of information is what firms desire in the RF model, while no disclosure is what firms choose in the AJ model can be verified by considering that spillovers are endogenous. Suppose that firms may have some power in deciding how much of the new knowledge they create becomes publicly available and thus useful to their competitors. Firm i chooses β_j. Poyago-Theotoky (1999) considers the AJ feedback mechanism and argues that firms will never disclose any of their information when they compete in R&D. Firms will choose the opposite in the RF model when $\beta_i > \frac{1}{2}$.

Proposition 3 (Endogenous spillovers) *In industries with RF mechanisms, firm choose to disclose their knowledge to their product market competitors as long as their R&D decisions are strategic complements. In industries with AJ mechanisms, firms will never disclose any of their information when they compete in R&D.*

If $\beta_i > \frac{1}{2}$, the second derivative $\frac{\partial^2 \pi_i}{\partial \beta_j^2}$ is positive, indicating that there are corner solutions. The profit-maximizing choice for a firm is information disclosure, $\beta_j = \overline{\beta}_j$. This result illustrates that regeneration of knowledge makes information sharing between firms a form of R&D cooperation. Thus, in industries in which the RF mechanism is regenerative, IP protection needs to be weaker, as R&D rivals are benefited by exchanging their research results. In this environment, firms will tend to form cooperative R&D agreements such as RJVs, which is also welfare improving.[18]

[18] For instance, biotechnology companies often form strategic alliances with pharmaceutical companies. Such

An alternative view would incorporate an absorptive capacity channel, as in Kamien & Zang (2000), to endogenize the incoming spillovers. Firms can have endogenous control over the outgoing spillovers from their R&D activity. At the one extreme, a firm's R&D approach can be firm specific: no spillovers are generated to its rivals because the information provided is not useful, and thus the firm's absorptive capacity is limited. At the other extreme, a basic R&D approach can be used: it generates the maximum spillovers to its rival. A firm also cannot realize benefits from spillovers from its rival's R&D without engaging in R&D itself. In a symmetric equilibrium, our results are in line with Kamien & Zang (2000). We can derive that when firms cooperate in the setting of their R&D investments - for instance, by forming an RJV - they choose identical broad R&D approaches. In contrast, when they compete in R&D, they choose firm-specific R&D approaches.

5 Conclusion

We examine firms' incentives to conduct cost-reducing R&D in high-technology industries in which asymmetric cross-firm R&D spillovers occur and feedback is regenerative. Due to spillovers, a firm can exploit the knowledge acquired through its own *as well as* its rival's research and build on it. We model this feedback mechanism whereby spillovers increase the effectiveness of each firm's R&D in reducing costs. Due to the cumulative nature of knowledge externalities, we argue that, if firms' R&D reaction curves are upward sloping, outgoing spillovers strengthen its optimal R&D incentives. Firms can exploit cross-firm spillovers and generate greater efficiency enhancements. In particular, by conducting more R&D, a firm increases its rival's R&D output through outgoing spillovers and indirectly contributes to its own R&D outcome. This is because this particular firm can internalize a share of the provided benefit with incoming spillovers. In contrast to the existing literature on exogenous spillovers, spillovers spur R&D even in markets with homogeneous products. We also analyze the effects of spillovers on welfare and discuss whether R&D competition or cooperation (RJVs) is welfare-enhancing given the characteristics of the innovation process and the feedback mechanism (AJ or RF) in a specific industry. One could extend this literature by considering the role of feedback mechanisms in sequential-move games instead of simultaneous move games (Amir, Amir & Jin (2000)' Amir & De Feo (2014)).

collaborations start early in the research process to allow the collaborators to share information, pre-clinical and clinical R&D costs. Prominent pharmaceutical companies, including Novartis, GlaxoSmithKline, and Aventis, are created by (horizontal) R&D mergers.

The empirical literature supports the idea that the development of knowledge-driven industries and technological parks such as Silicon Valley exploits feedback mechanisms that exhibit increasing returns to spillovers. In "learning" regions and industries in which innovation is rushed and knowledge is defused during the innovation process, individuals and firms exploit regenerative feedback mechanisms. This model can be used to interpret empirical evidence on the R&D performance of modern corporations in these industries. Science-based firms operating in rapidly changing high technology industries differ in culture, behavior, management techniques, and strategies from those operating in industries in which communication during the innovation process is limited. In the latter type of creative environment, the R&D process can be captured by feedback mechanisms, as in D'Aspremont & Jacquemin (1990) and Kamien, Muller & Zang (1992). Firms autonomously invest in R&D, and outgoing spillovers only have detrimental effects on the innovator's profits, decreasing R&D.

The challenge for policy makers and entrepreneurs is to be aware of the differences in technical advances arising due to different mechanisms of knowledge diffusion. R&D policies and future research on firms' strategies have to take into account the special economics of positive and regenerative feedback mechanisms. Given the characteristics of high technology industries, government policies must be adjusted to facilitate the "right" degree of knowledge diffusion. In markets with RF mechanisms, policies that decrease firms' intellectual property rights protections or encourage an exchange of ideas will allow innovators to seize additional knowledge and achieve better R&D outcomes. Policy makers must be aware of such feedback mechanisms and build an environment consisting of actors and institutions intended to foster innovation and economic growth. The legal framework should also facilitate collaboration between research units.

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A APPENDIX

A.1 Proof of Lemma 1

We take firm i's and j's first-order conditions in the second stage of the game and differentiate them with respect to x_i. We get, respectively,

$$\frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i}+\frac{\partial^2 \pi_i}{\partial q_j \partial q_i}\frac{\partial q_j}{\partial x_i}=-\frac{\partial^2 \pi_i}{\partial c_i \partial q_i}\frac{\partial c_i}{\partial x_i}, \tag{10}$$

$$\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\frac{\partial q_i}{\partial x_i}+\frac{\partial^2 \pi_j}{\partial q_j^2}\frac{\partial q_j}{\partial x_i}=-\frac{\partial^2 \pi_j}{\partial c_j \partial q_j}\frac{\partial c_j}{\partial x_i}. \tag{11}$$

Given that $\frac{\partial^2 \pi_i}{\partial c_i \partial q_i}=\frac{\partial^2 \pi_j}{\partial c_j \partial q_j}=-1$, we solve them and obtain the derivatives

$$\frac{\partial q_j}{\partial x_i}=\frac{1}{\Omega}\left(\frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial c_j}{\partial x_i}-\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\frac{\partial c_i}{\partial x_i}\right), \tag{12}$$

$$\frac{\partial q_i}{\partial x_i}=\frac{1}{\Omega}\left(\frac{\partial^2 \pi_j}{\partial q_j^2}\frac{\partial c_i}{\partial x_i}-\frac{\partial^2 \pi_i}{\partial q_j \partial q_i}\frac{\partial c_j}{\partial x_i}\right)>0,$$

where $\Omega \equiv \frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial^2 \pi_j}{\partial q_j^2}-\frac{\partial^2 \pi_j}{\partial q_j \partial q_i}\frac{\partial^2 \pi_i}{\partial q_i \partial q_j}>0$ is implied from the stability condition. Given that $\left|\frac{\partial c_i}{\partial x_i}\right|>\left|\frac{\partial c_i}{\partial x_j}\right|$, the sign of the derivative $\frac{\partial q_i}{\partial x_i}$ follows from the assumption $\frac{\partial^2 \pi_i}{\partial q_i^2}<\left|\frac{\partial^2 \pi_i}{\partial q_i \partial q_j}\right|$. The derivative $\frac{\partial q_j}{\partial x_i}$ is positive when the condition in Lemma 1 holds.

A.2 Proof of Lemma 2

To derive the slope of firm i's R&D best-response curve when firms compete in quantities, we totally differentiate the first order condition $\frac{\partial \Pi_i}{\partial x_i}=\frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i}+\frac{\partial \pi_i}{\partial c_i}\frac{\partial c_i}{\partial x_i}-g_i'=0$ and obtain:

$$\left\{\frac{\partial^2 \pi_i}{\partial q_j^2}\left(\frac{\partial q_j}{\partial x_i}\right)^2+\frac{\partial^2 \pi_i}{\partial q_j \partial q_i}\frac{\partial q_i}{\partial x_i}\frac{\partial q_j}{\partial x_i}+\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 q_j}{\partial x_i^2}+\frac{\partial^2 \pi_i}{\partial c_i \partial q_i}\frac{\partial q_i}{\partial x_i}\frac{\partial c_i}{\partial x_i}-g''(x_i)\right\}dx_i+$$
$$\left\{\frac{\partial^2 \pi_i}{\partial {q_j}^2}\frac{\partial q_j}{\partial x_j}\frac{\partial q_j}{\partial x_i}+\frac{\partial^2 \pi_i}{\partial q_j \partial q_i}\frac{\partial q_i}{\partial x_j}\frac{\partial q_j}{\partial x_i}+\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 q_j}{\partial x_i \partial x_j}+\frac{\partial^2 \pi_i}{\partial c_i \partial q_i}\frac{\partial q_i}{\partial x_j}\frac{\partial c_i}{\partial x_i}\right\}dx_j=0.$$

The coefficient of dx_i is negative from the second order condition. We denote it by $\Delta<0$. Given also that $\frac{\partial^2 q_j}{\partial x_i^2}=0$ and $\frac{\partial^2 q_j}{\partial x_i \partial x_j}=0$, the above expression reduces to equation

$$\Delta dx_i+\left[\frac{\partial^2 \pi_i}{\partial q_j^2}\frac{\partial q_j}{\partial x_j}\frac{\partial q_j}{\partial x_i}+\left(\frac{\partial^2 \pi_i}{\partial q_j \partial q_i}\frac{\partial q_j}{\partial x_i}+\frac{\partial^2 \pi_i}{\partial c_i \partial q_i}\frac{\partial c_i}{\partial x_i}\right)\frac{\partial q_i}{\partial x_j}\right]dx_j=0. \tag{13}$$

By (10), we have $\frac{\partial^2\pi_i}{\partial q_j \partial q_i}\frac{\partial q_j}{\partial x_i} + \frac{\partial^2\pi_i}{\partial c_i \partial q_i}\frac{\partial c_i}{\partial x_i} = -\frac{\partial^2\pi_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i} > 0$. Thus, equation (13) becomes

$$\frac{dx_i}{dx_j} = -\frac{1}{\Delta}\left[\frac{\partial^2\pi_i}{\partial q_j^2}\frac{\partial q_j}{\partial x_j}\frac{\partial q_j}{\partial x_i} - \frac{\partial^2\pi_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i}\frac{\partial q_i}{\partial x_j}\right],$$

implying that firms' R&D decisions are strategic complements, $\frac{dx_i}{dx_j} > 0$, when the summation in the parenthesis and thus the condition in Lemma 2 holds.

A.3 Proof of Proposition 1

We totally differentiate firm j's first-order condition with respect to β_j and get

$$T_j + H_j\frac{dx_i^R}{d\beta_j} + \delta_j\frac{dx_j^R}{d\beta_j} = 0, \tag{14}$$

where

$$T_j \equiv \frac{\partial\pi_j}{\partial q_i}\frac{\partial^2 q_i}{\partial x_j \partial\beta_j} + \frac{\partial\pi_j}{\partial c_j}\frac{\partial^2 c_j}{\partial x_j \partial\beta_j} + \frac{\partial^2\pi_j}{\partial q_i \partial\beta_j}\frac{\partial q_i}{\partial x_j} + \frac{\partial^2\pi_j}{\partial c_j \partial\beta_j}\frac{\partial c_j}{\partial x_j}. \tag{15}$$

Solving the equations (2) and (14), we get

$$\frac{dx_i^R}{d\beta_j} = \frac{H_iT_j - T_i\delta_j}{\delta_i\delta_j - H_iH_j},$$

which is positive because $\delta_i\delta_j - H_iH_j > 0$, $H_i > 0$, $T_j > 0$, $T_i > 0$ and $\delta_j < 0$.

A.4 Proof of Proposition 2

Suppose that there is some degree of substitutability between the firms' goods and the Cournot demand is given by $p = a - q_i - bq_j$, where $b \in (0, 1)$. For a product market that involves Bertrand competition, we rewrite the Cournot demand with respect to prices and obtain $q_i = \frac{a}{1+b} - \frac{p_i - bp_j}{1-b^2}$. We first solve the Bertrand game and obtain firm i's equilibrium price: $p_i = \frac{a(1-b)}{2-b} + \frac{2c_i + bc_j}{4-b^2}$. After the realization of marginal costs, firm i's Bertrand profit is $\pi_i^B = (1-b^2)\, q_{i,B}^2 - g(x_{i,B})$, where $q_i^B = \frac{\alpha - \bar{c}}{(2-b)(1+b)} + \frac{\left[2-b\left(b+\beta_j\right)\right]x_i^B - \left[b-\beta_i\left(2-b^2\right)\right]x_j^B}{(4-b^2)(1-b^2)\left(1-\beta_i\beta_j\right)}$. Thus, if $\frac{b}{2-b^2} > \beta_i$, firm i's R&D reaction curve is downward sloping, while the opposite holds when $\beta_i > \frac{b}{2-b^2}$. In period 1, we take firm i's first-order condition and then totally differentiate it with respect to β_j. It implies

$$\frac{2\left[2-b\left(b+\beta_i\right)\right]}{\left(4-b^2\right)\left(1-\beta_i\beta_j\right)^2}\left[\beta_i q_j^B + \lambda_j\left(\beta_i x_j^B + x_i^B\right) + \frac{\left(2-b^2\right)\beta_j - b}{\left(4-b^2\right)\left(1-b^2\right)}\frac{dx_i^B}{d\beta_j}\right] + \zeta_i\frac{dx_j^B}{d\beta_j} = 0, \tag{16}$$

where $\zeta_j \equiv \frac{4[2-b(b+\beta_i)]^2}{(1-b^2)(4-b^2)^2\left(1-\beta_i\beta_j\right)^2} - g'' < 0$ and $\lambda_i \equiv \frac{2-b\left(b+\beta_j\right)}{(4-b^2)(1-b^2)\left(1-\beta_i\beta_j\right)}$. Similarly, the decomposition of firm j's optimal incentives yields

$$\frac{2\left[\left(2-b^2\right)\beta_j - b\right]}{\left(4-b^2\right)\left(1-\beta_i\beta_j\right)^2}\left[q_j^B + \lambda_j\left(x_j^B + \beta_j x_i^B\right) + \frac{2-b\left(b+\beta_i\right)}{\left(4-b^2\right)\left(1-b^2\right)}\frac{dx_i^B}{d\beta_i}\right] + \zeta_j\frac{dx_j^B}{d\beta_i} = 0. \qquad (17)$$

We solve equations (16) and (17) and obtain

$$\frac{dx_i^B}{d\beta_j} = \frac{2\left[\left(2-b^2\right)\beta_i - b\right]\Phi_i}{\Delta_B\left(1-b^2\right)^2\left(4-b^2\right)\left(1-\beta_i\beta_j\right)^2},$$

where

$$\begin{aligned}
\Phi_i &\equiv \frac{2\lambda_i\lambda_j}{1-b^2}\left[\beta_i q_j^B + \lambda_j\left(\beta_i x_j^B + x_i^B\right)\right] - \zeta_j\left[q_i^B + \zeta_i\left(x_i^B + \beta_i x_j^B\right)\right], \\
\Delta_B &= \zeta_i\zeta_j - \frac{4\lambda_i\lambda_j\left[\left(2-b^2\right)\beta_i - b\right]\left[\left(2-b^2\right)\beta_j - b\right]}{\left(1-b^2\right)^2\left(1-\beta_i\beta_j\right)^2}.
\end{aligned}$$

Given that $\Delta_B > 0$ from the stability condition and $\Phi_i > 0$, we have $\frac{dx_i^B}{d\beta_j} > 0$ if and only if $\beta_i > \frac{b}{2-b^2}$, guaranteeing that R&D decisions are strategic substitutes.