Spillover feedback loops and strategic complements in R&D

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Abstract

This paper studies, in a two period model, the effects of knowledge spillovers among product market competitors on R&D levels. It argues that when firms' R&D decisions are strategic complements, in industries in which spillovers increase the marginal productivity of a firm's R&D, both incoming *and* outgoing spillovers spur R&D in equilibrium. Outgoing spillovers can foster innovation even in a homogeneous-product industry. In these industries, the IP law should be such that facilitates knowledge diffusion. If firms have power in deciding the level of knowledge spillovers, we show that a firm will choose to disclose its knowledge to its product market competitors.

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

JEL: L13, O31, O33

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*I am indebted to Lambros Pechlivanos for the very useful discussions on this topic. I am also grateful to Rabah Amir, Dan Bernhardt, George Deltas, Chrysovalantou Milliou, Katharine Rockett, Konstantinos Serfes and Spyros Vassilakis for their comments and suggestions. I give special thanks to Claude D'Aspremont, Raymond De Bondt, Mehmet Ekmekci, Vitor Farinha, Gianluca Femminis, Johannes Hörner, Sebastian Kranz, Silvana Krasteva, Vijay Krishna, Ana Rodrigues, Larry Samuelson, Philipp Strack, Rodrigo Velez, Nicolaos Vettas, and the participants at various conferences and meetings.

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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. Levin (1988) studies the effect of spillovers on R&D activity and states that there are differences in technical advances in different high-technology 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 precisely these industries in which feedback is regenerative and argue that when a firm's R&D decision is a strategic complement, larger outgoing spillovers foster innovation. In these industries, the intellectual property (IP) policies should facilitate knowledge diffusion rather than putting limitations. If the spillover rates are assumed to be endogenous, firms will choose to disclose their knowledge to their product market competitors.

In the regenerative feedback model (RF model, hereafter), 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.

We study cost-reducing R&D incentives in a two-period model in which firms first indepen-

[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.

dently 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. Amir (2000) and Amir, Amir & Jin (2000) study in depth the distinction between strategic complements and substitutes in R&D and how this connects to spillovers. When a firm's R&D decision is a strategic complement, the firm's 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.[3] 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 acquire 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 linear demand and convex cost functions and specify the conditions under which outgoing spillovers foster R&D in equilibrium. 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: the innovative firm's R&D decision needs to be a strategic complement.[4]

Existing models with exogenous spillovers, based on D'Aspremont & Jacquemin (1988) (AJ model, hereafter) 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 these models, outgoing spillovers always induce homogeneous-product rivals to conduct *less* R&D in equilibrium. Outgoing spillovers harm the innovative firm and decrease its optimal R&D. Rockett (2012) provides

[3] 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.

[4] We can show that it does *not* depend on the mode of competition in the product market: as long as firms' R&D best-response curves are upward sloping, outgoing spillovers can stimulate R&D in both Cournot and Bertrand settings.

an excellent summary.[5] The conventional wisdom in this literature is that spillovers inhibit the attainment of a competitive advantage, and the severity of the free-rider problem induces firms to reduce investment in R&D as spillovers increase. This result does not hold when the feedback is regenerative. Instead, when a firm's best-response function is upward sloping, outgoing spillovers stimulate R&D.

This paper is also related to the 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, or network externalities (Choi (1993)). The recombination of knowledge has also 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 spillover rates are exogenous and asymmetric.[6]

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) show under what conditions firms' R&D decisions are strategic substitutes or complements and examine when firms innovate more as leaders or followers compared to what they do in a simultaneous move game. 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

[5] Cosandier, Feo & Knauff (2017) consider one-way spillovers from a high R&D firm to a low R&D firm. They examine the conditions under which ex-ante identical firms will choose asymmetric R&D investments, resulting in interfirm heterogeneity in the industry. Cassiman & Veugelers (2006) study firms' ability in external knowledge acquisition. 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. Chalioti & Serfes (2017) analyze how managerial risk affects firms' incentives to invest in cost-reducing R&D. 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.

[6] 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.

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] Future research on R&D activity needs to identify and take into account 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, we may also expect firms to engage in collusive-like behavior and form research joint ventures (RJV) in order to internalize knowledge flows (Bernstein & Nadiri (1989), Bloom, Schankerman & Van Reenen (2013)).[8] A policy implication of the RF model would be the IP protection to be weakened. 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.

We also analyze firms' equilibrium decisions when spillovers are endogenous. Firms now can choose how much of their research results will become publicly available. Poyago-Theotoky (1999) shows that in the AJ model, firms will never disclose any of their information when they compete in R&D. Thus, firms desire to protect themselves against spillovers. In the RF model, firms seek to exchange their knowledge. Amir, Evstigneev & Wooders (2003) consider a general version of a two-stage model of R&D and characterize the structure of R&D cartels where product market rivals jointly decide R&D expenditures and internal spillovers rates. They show that firms would always prefer external spillovers, and derive the conditions under which minimal spillovers are optimal.[9]

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 and derive the equilibrium R&D levels. We also decompose both firms' R&D incentives to analyze the effects of spillovers

[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 protection in different countries and whether there are international mechanisms to repatriate the spillovers they generate.

[9] McDonald & Poyago-Theotoky (2017) study emission policies. They examine the impact of an optimal emissions tax on R&D of emission reducing green technology in the presence of input spillovers (only knowledge spillovers are accounted) and output spillovers (both abatement and knowledge spillovers co-exist). They argue that the optimal emissions tax required to foster R&D is higher in the presence of input spillovers.

on equilibrium R&D. In Section 4, we compare the relationship between outgoing spillovers and equilibrium R&D in the RF and AJ models. We highlight the policies implications of both models and study firms' choices to disclose their knowledge when the spillover rates are endogenous. Section 5 concludes.

2 The model

The market features two profit-seeking firms, indexed by i and j, where $i \neq j$. These firms interact for two periods, indexed by $t = \{1, 2\}$, and play the game described in Figure 1.

Period 1 *R&D stage:*	$\longrightarrow$	*Production stage:*	$\longrightarrow$	Period 2 *R&D stage:*	$\longrightarrow$	*Production stage:*
Firms simultaneously invest in cost-reducing innovation and choose x_1^i, x_1^j.		Firms compete à la Cournot in the product market for consumers, and produce q_1^i, q_1^j.		Given the existing knowledge, firms conduct innovation, x_2^i and x_2^j, in the presence of spillovers.		Firms engage in Cournot competition and choose q_2^i, q_2^j.

Figure 1. Timing of the game

The market is populated by a continuum of identical consumers with mass equal to 1. There is no discounting and at each period t, the representative consumer's utility function is $U(q_t^i, q_t^j) = a\left(q_t^i + q_t^j\right) - \left[\frac{1}{2}\left(q_t^i\right)^2 + \frac{1}{2}\left(q_t^j\right)^2 + q_t^i q_t^j\right]$ as in Singh & Vives (1984), where a denotes the market size, $a > 0$, and q_t^i is firm i's output.[10,11] Thus, each firm i produces a homogeneous good and faces the demand $p_t^i = a - q_t^i - q_t^j$, where p_t^i denotes its price.

Firms initially have marginal cost $\bar{c}$, where $a > \bar{c} > 0$, but can reduce it by investing in process innovation. In particular, firm i's per-period effective (final) marginal cost is $c_t^i = \bar{c} - y_t^i$, where y_t^i denotes the R&D output at any period t. In period 1, firm i carries out its own project, chooses x_1^i, which is also its R&D output, $y_1^i = x_1^i$.[12] Similarly, firm j's R&D output is $y_1^j = x_1^j$. In period 2, firms can take advantage of the existing knowledge as well as of the presence of R&D spillovers. In particular, firm i's R&D output depends on the stock of knowledge that has been created by

[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. Because the profit functions with process and product innovation are the same, the equilibrium R&D decisions and comparative statics hold in both settings (Vives (2008)).

[12] One can consider that spillovers also occur in period 1. Our result that there is a positive effect of outgoing spillovers on a firm's equilibrium R&D level *still holds*. We consider that spillovers are present only in period 2 in order to highlight the dynamics of the diffusion process. Outside knowledge also feeds and interact with a firms' current and previous ideas, and builds upon in subsequent periods.

firm i in the past, firm i's current R&D level and to some extent on the rival's R&D output:

$$y_2^i = x_1^i + x_2^i + \beta_i y_2^j,\ \forall i,\ j. \tag{1}$$

The parameter 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. The parameter β_i is exogenous and lies in $\left[0, \overline{\beta}_i\right]$, where $\overline{\beta}_i < 1$. 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 its rival's. Unless firms have created a research joint venture or agreed upon information sharing, spillovers are imperfect in any market with some degree of IP protection. This is also the case when reverse engineering does not reveal all information regarding the underlying technology or, for example, when firms hide some research results and delay publications. Thus, there is some redundancy between a firm's own R&D and the appropriation of its rival's research findings. Substituting $y_2^j = x_1^j + x_2^j + \beta_j y_2^i$ into equation (1) implies

$$y_2^i = \frac{\sum_{t=1}^{2} x_t^i + \beta_i \sum_{t=1}^{2} x_t^j}{1 - \beta_i \beta_j}. \tag{2}$$

The feasibility bound that guarantees positive post-innovation marginal costs take the form $\overline{x_2^i}\left(x_2^j\right) = \left(1 - \beta_i \beta_j\right)\overline{c} - x_1^i - \beta_i\left(x_1^j + x_2^j\right)$ for any i and j. Firm i will commit to an R&D level $x_2^i \in \Omega$, where $\Omega \equiv \left[0, \left(1 - \beta_i \beta_j\right)\overline{c}\right]$.

The RF mechanism indicates that firm i's R&D output, which depends on the outcome of firm i's current research as well as on the stock of knowledge firm i acquired in the past, 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 its rival's research output that has already been developed using its own R&D results. Thus, each firm exploits the existing knowledge that created in the previous period by both firms and adds to it. The innovator improves the other firm's research outcome, but she can receive back some benefits in technological advancement that she initiated. 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. 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.

D'Aspremont & Jacquemin (1988) consider that there are no interactions between the firms during the innovation process, and the innovator cannot internalize any benefit from outgoing spillovers. Thus, β_j does not affect the effectiveness of a firm's own R&D in enhancing efficiency. However, we consider a different knowledge spillover mechanism that can occur in industries where innovation is a "building block" and the feedback is regenerative; β_j increases the marginal productivity of x_1^i and x_2^i on reducing costs.

To acquire the R&D level x_t^i, firm i incurs the R&D cost $g(x_t^i)$, where $g(0) = 0$, $g'(0) = 0$ and $\lim_{x_t^i \to \infty} g'(x_t^i) = \infty$. 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 R&D levels and examine the effects of spillovers on them by considering general cost functions.

3 RF mechanism and R&D incentives

In each period, firms first simultaneously conduct R&D and then engage in Cournot competition. We recursively solve this two-period game and derive the equilibrium R&D incentives. We also perform a comparative statics analysis to examine the effect of spillovers on R&D.

3.1 Equilibrium R&D investments

In period 2, each firm i maximizes $\Pi_2^i = \left(a - q_2^i - q_2^j - c_2^i\right) q_2^i$. It produces the output

$$q_2^i = \frac{1}{3}\left(a - 2c_2^i + c_2^j\right), \tag{3}$$

and receives $\Pi_2^i = \left(q_2^i\right)^2$. Before firms compete for market share, they innovate in the presence of spillovers and each firm i maximizes its 'Cournot' profit net its cost of doing R&D, $\pi_2^i =$

$(q_2^i)^2 - g(x_2^i)$. By equations (2) and (3), the equilibrium output becomes

$$q_2^i = \frac{1}{3}\left[a - \overline{c} + \gamma_i\left(x_1^i + x_2^i\right) + \frac{2\beta_i - 1}{1 - \beta_i\beta_j}\left(x_1^j + x_2^j\right)\right], \tag{4}$$

where $\gamma_i \equiv \frac{2-\beta_j}{1-\beta_i\beta_j}$. The slope of firm i's R&D best-response curve depends on the sign of $\frac{\partial^2 \pi_2^i}{\partial x_2^i \partial x_2^j} = \frac{2\gamma_i(2\beta_i - 1)}{9\left(1-\beta_i\beta_j\right)}$. If the incoming spillovers are small so that $\beta_i < \frac{1}{2}$, firm i's R&D best-response 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.

To guarantee that there exists an interior equilibrium in R&D, the following Inada-type assumptions on the profit function π_2^i need to hold:[13]

$(R.1)$ $\delta_{i,R} \equiv \frac{4}{9}\gamma_i^2 - g''\left(x_2^i\right) < 0, \forall i, j$

$(R.2)$ $\Delta_R \equiv \delta_{i,R}\delta_{j,R} - \frac{4\gamma_i\gamma_j}{81\left(1-\beta_i\beta_j\right)^2}\left(2\beta_i - 1\right)\left(2\beta_j - 1\right) > 0,$

where the superscript R denotes values in the RF model. Assumptions $(R.1)$ and $(R.2)$ require a strong form of convexity of the cost-of-R&D functions to guarantee that each firm's profit function is concave in its own R&D and the stability conditions hold. They also set a lower bound on the unit cost of doing R&D so that the post-innovation marginal costs are positive. Firm i's equilibrium R&D decision satisfies $\frac{2\gamma_i}{3}q_{2,R}^i = g'(x_{2,R}^i)$, where $q_{2,R}^i$ is given in equation (4). Solving the first-order conditions of the maximization problem of both firms, we obtain the equilibrium $x_{2,R}^{i*}$ and $x_{2,R}^{j*}$, as functions of the first-period R&D levels. In period 1, firm i maximizes

$$\pi_1^i + \pi_2^{i*}\left(x_{2,R}^{i*}\right) = \frac{1}{9}\left(a - \overline{c} + 2x_1^i - x_1^j\right)^2 - g(x_1^i) + \frac{9}{4\gamma_i^2}\left[g'(x_{2,R}^{i*})\right]^2 - g(x_{2,R}^{i*}), \tag{5}$$

where $q_2^{i*}\left(x_{2,R}^{i*}\right) = \frac{3}{2\gamma_i}g'(x_{2,R}^{i*})$. Each firm anticipates that the stock of knowledge created in the first period will affect the R&D production in the second period. The optimal $x_{1,R}^{i*}$ satisfies the condition

$$\frac{4}{3}q_{1,R}^{i*} - g'(x_{1,R}^{i*}) + \left[\frac{9}{2\gamma_i^2}g''(x_{2,R}^{i*}) - 1\right]g'(x_{2,R}^{i*})\frac{dx_{2,R}^{i*}}{dx_1^i} = 0. \tag{6}$$

The solution of both firms' first-order conditions gives the equilibrium $x_{1,R}^{i*}$ and $x_{1,R}^{j*}$. We can

[13]The market parameter a needs to be substantially higher than c so that both firms have incentives to conduct some R&D. The unit cost of R&D is also assumed to be large so that the slopes of the R&D reaction functions lie between -1 and 1.

analyze the effects of spillovers on the optimal R&D incentives without deriving an explicit form for their levels.

3.2 R&D intensity and spillovers

We show that in the RF model, if a firm's R&D best-response curve is upward sloping, larger outgoing spillovers boost its own R&D. This result counters the prediction of the existing literature based on the AJ model that outgoing spillovers always diminish optimal R&D. We show that such motives are reversed when the feedback is reinforced.

To understand rivals' strategic R&D motives, we decompose the underlying effects of R&D:

$$\frac{\partial \pi_2^i}{\partial x_2^i} = \frac{\partial \Pi_2^i}{\partial q_2^j}\frac{\partial q_2^j}{\partial x_2^i} + \frac{\partial \Pi_2^i}{\partial c_2^i}\frac{\partial c_2^i}{\partial x_2^i} - g'(x_2^i). \tag{7}$$

There is a direct effect on cost reduction, $\frac{\partial \Pi_2^i}{\partial c_2^i}\frac{\partial c_2^i}{\partial x_2^i} = \frac{1}{1-\beta_i\beta_j} q_2^i$, and an indirect effect due to product market competition which is captured by[14]

$$\frac{\partial \Pi_2^i}{\partial q_2^j}\frac{\partial q_2^j}{\partial x_2^i} = \frac{\partial \Pi_2^i}{\partial q_2^j}\frac{1}{\Theta\left(1-\beta_i\beta_j\right)}\left[\frac{\partial^2 \Pi_2^j}{\partial q_2^i \partial q_2^j} - \beta_j \frac{\partial^2 \Pi_2^i}{\partial \left(q_2^i\right)^2}\right] = \frac{1-2\beta_j}{3\left(1-\beta_i\beta_j\right)} q_2^i, \tag{8}$$

where $\Theta \equiv \frac{\partial^2 \Pi_2^i}{\partial \left(q_2^i\right)^2}\frac{\partial^2 \Pi_2^j}{\partial \left(q_2^j\right)^2} - \frac{\partial^2 \Pi_2^i}{\partial q_2^j \partial q_2^i}\frac{\partial^2 \Pi_2^j}{\partial q_2^i \partial q_2^j} > 0$. 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 the rival in the product market. When the outgoing spillovers are large so that $\beta_j > \frac{1}{2}$, the latter effect dominates the former and a firm's R&D will induce its competitor to innovate more, making rival's R&D best-response curve upward sloping. Firm j's R&D decision will be a strategic complement. In equilibrium, there is a trade-off among all these effects against the cost of doing R&D.

When firms' R&D decisions are strategic complements, an increase in a firm's R&D elicits an increased R&D investment from the other and firms' main objective is precisely to reduce

[14] Firm i's first-order condition for its output is $\frac{\partial \Pi_2^i}{\partial q_2^i} = p_2^i + q_2^i \frac{\partial p_2^i}{\partial q_2^i} - c_2^i = 0$. Differentiating both firms' conditions with respect to x_2^i yields $\frac{\partial^2 \Pi_2^i}{\partial \left(q_2^i\right)^2}\frac{\partial q_2^i}{\partial x_2^i} + \frac{\partial^2 \Pi_2^i}{\partial q_2^j \partial q_2^i}\frac{\partial q_2^j}{\partial x_2^i} = -\frac{1}{1-\beta_i\beta_j}$ and $\frac{\partial^2 \Pi_2^j}{\partial q_2^i \partial q_2^j}\frac{\partial q_2^i}{\partial x_2^i} + \frac{\partial^2 \Pi_2^j}{\partial \left(q_2^j\right)^2}\frac{\partial q_2^j}{\partial x_2^i} = -\frac{\beta_j}{1-\beta_i\beta_j}$, implying equation (8).

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 RF mechanism. Proposition 1 establishes that the more knowledge a firm is able to initiate and then reabsorb from another firm's research, the more R&D this firm acquires itself.[15]

Proposition 1 (R&D incentives and regenerative feedback) *In the RF model, firm i's equilibrium second period R&D level increases with outgoing spillovers, $\frac{dx^{i*}_{2,R}}{d\beta_j} > 0$, when incoming spillovers to firm i are large so that its R&D decision is a strategic complement, $\beta_i > \frac{1}{2}$.*

Proof. In Appendix $(A.1)$. ■

Firm i's research will allow firm j to produce a better R&D output that will be diffused back, improving firm i's R&D performance even further. This result requires the effects of outgoing spillovers on a firm's cost enhancement to be more significant compared to the strategic benefits of R&D in terms of market share. In industries with RF mechanism, firms innovate more and achieve greater efficiencies in production. The aggregate innovation and production levels will also increase.

To better understand Proposition 1, we totally differentiate each firm's first-order condition with respect to β_j. In particular, taking $\frac{d\left(\partial\pi^i_2/\partial x^i_2\right)}{d\beta_j} = 0$, we get $\frac{\partial\left(\partial\pi^i_2/\partial x^i_2\right)}{\partial\beta_j} + \frac{\partial^2\pi^i_2}{\partial\left(x^i_2\right)^2}\frac{dx^{i*}_{2,R}}{d\beta_j} = 0$, where $\frac{\partial^2\pi^i_2}{\partial\left(x^i_2\right)^2} = \frac{2}{9}\gamma_i^2 - g''\left(x^{i*}_{2,R}\right) < 0$ by assumption $(R.1)$. Thus, as spillovers are intensified, a firm's optimal R&D will increase in the regime where the marginal profitability of R&D is also increasing. The decomposition of firm i's optimal R&D incentives with respect to β_j gives

$$\frac{2\left(2\beta_i-1\right)}{9\left(1-\beta_i\beta_j\right)^2}\left[\underbrace{3q^{i*}_{2,R}}_{\text{output effect}} + \underbrace{\gamma_i\sum_{t=1}^{2}x^{i*}_{t,R}}_{\text{own-R\&D effect}} + \underbrace{\gamma_i\beta_i\sum_{t=1}^{2}x^{j*}_{t,R}}_{\text{rival-R\&D effect}} + \left(2-\beta_j\right)\frac{dx^{j*}_{2,R}}{d\beta_j}\right] + \delta_{i,R}\frac{dx^{i*}_{2,R}}{d\beta_j} = 0. \quad (9)$$

Equation (9) shows that when $\beta_i > \frac{1}{2}$, *outgoing* spillovers give rise to three *positive* effects. First, there is the *output* effect: if incoming spillovers are large enough, outgoing spillovers increase the marginal contribution of x_i to firm i's production output: $\frac{\partial\left(\partial q^i_2/\partial x^i_2\right)}{\partial\beta_j} > 0$ for any β_i and β_j. Second, there is the *own-R&D* effect: when $\beta_i > \frac{1}{2}$, as outgoing spillovers increase, a firm's past

[15] In the online Appendix, we show that in the RF model, a positive relationship between outgoing spillovers and equilibrium R&D also holds for Bertrand rivals with differentiated products, when the innovator's R&D best-response curve is upward sloping. This result does not depend on the mode of competition in the product market. Note that in some innovation settings, the mode of competition may critically matter (see e.g., Niu (2018)).

and current R&D become more effective in cost reduction. Because of outgoing spillovers, the firm improves its rival's research output but can now absorb some part of it 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 $\beta_i > \frac{1}{2}$, firm j's R&D conducted in both periods now becomes increasingly more significant in firm i's production and equilibrium profits. Thus, as long as the incoming spillovers are also large, in industries with RF mechanisms, the more knowledge a firm appropriates from another firm's research or even initiate, the more R&D this firm acquires itself. Larger outgoing (and incoming) spillovers increase the marginal productivity of both firms' R&D, conducted in the current and previous periods, motivating firm i to do more R&D itself. In AJ model, 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.

Suppose now that firm i absorbs more know-how from its opponent so that its R&D decision is a strategic complement, $\beta_i > \frac{1}{2}$, while firm j's R&D decision is a strategic substitute, $\beta_j < \frac{1}{2}$. This model shows that outgoing spillovers induce a firm with an upward sloping R&D best-response curve to increase its own R&D in equilibrium, even when its rival's best-response curve is downward sloping. Cost reduction remains firm i's main goal, which can be achieved by conducting more R&D as outgoing spillovers increase, even though firm j will now invest less in R&D.

We can also consider the case in which both 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 for both firms. An increase in a firm's R&D dampens the R&D investment of the other. A firm now wants to have a strong strategic position, since its profitability mainly depends on the extent of its business; i.e., the strategic effect of R&D on the innovator's profit, in (7), is stronger than the efficiency effect. Larger outgoing spillovers, β_j, now 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 increase a firm's optimal R&D for all β_i and β_j. 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. Each firm has incentives to innovate in order to realize a lower marginal cost from its rival and take away its business. As β_i increases, firm i's R&D benefits its rival through knowledge diffusion and it gets harder for the innovator to steal market share when a rival can "catch up" readily due to knowledge flows, imposing a competitive threat against the R&D taking firm. Given that both firms have the same incentives, they are involved in a prisoners' dilemma type of game. Thus, firms' appetite for innovation increases with incoming spillovers in order to secure a cost advantage. A firm (or a technology) that gains an advantage has incentives to gain a further advantage.

4 Discussion

Section 4 illustrates the main results by comparing the RF and AJ models. It analyzes policy implications of both models and studies firms' decisions to disclose information about their technologies when the spillover rates are endogenous.

4.1 Comparison of RF and AJ models

We now discuss the equilibrium R&D incentives in D'Aspremont & Jacquemin (1988), and compare them with those in the RF model. Both models share the same features in the product market, implying that firm i's output in each model is given by equation (3). Thus, we focus on the R&D decisions in the AJ model and examine the effects of spillovers.

In the AJ model, a firm's findings are obtained autonomously and the innovator cannot internalize any benefit from outgoing spillovers. The stock of knowledge created by a rival in the past has no use in a firm's R&D process in the current period and β_j does not affect the effectiveness of a firm's own R&D in enhancing efficiency, $\frac{\partial^2 y_i^A}{\partial x_2^i \partial \beta_j} = 0$. Thus, a firm acts as if their rival "starts from scratch" every period. Firm i's effective R&D output is

$$y_2^i = x_1^i + x_2^i + \beta_i x_2^j. \tag{10}$$

The counterpart of equation (9) is

$$\underbrace{-\frac{2}{3} q_{2,A}^{i*}}_{\text{output effect}} + \frac{2}{9}\left(2-\beta_j\right)\left[\underbrace{-x_{2,A}^{i*}}_{\text{own-R\&D effect}} + \left(2\beta_i - 1\right)\frac{dx_{2,A}^{j*}}{d\beta_j}\right] + \delta_{i,A}\frac{dx_{2,A}^{i*}}{d\beta_j} = 0, \tag{11}$$

where $\delta_{i,A} \equiv \frac{4}{9}\left(2-\beta_j\right)^2 - g''\left(x_2^i\right) < 0$. The subscript A denotes values in the AJ model.

Proposition 2 (D'Aspremont & Jacquemin, 1988) *In the AJ model, firm i's equilibrium* *second period R&D level decreases with outgoing spillovers;* $\frac{dx^{i*}_{2,A}}{d\beta_j} < 0$*, for all* β_i *and* β_j*.*

Proof. In Appendix $(A.2)$. ■

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, harming firm i. Thus, in equilibrium, the innovator undertakes less R&D to diminish its rival's gains from knowledge diffusion. In the AJ model, outgoing spillovers decrease a firm's equilibrium R&D, regardless of the nature of R&D strategic interactions.

Figure 2. Effects of outgoing spillovers on equilibrium R&D

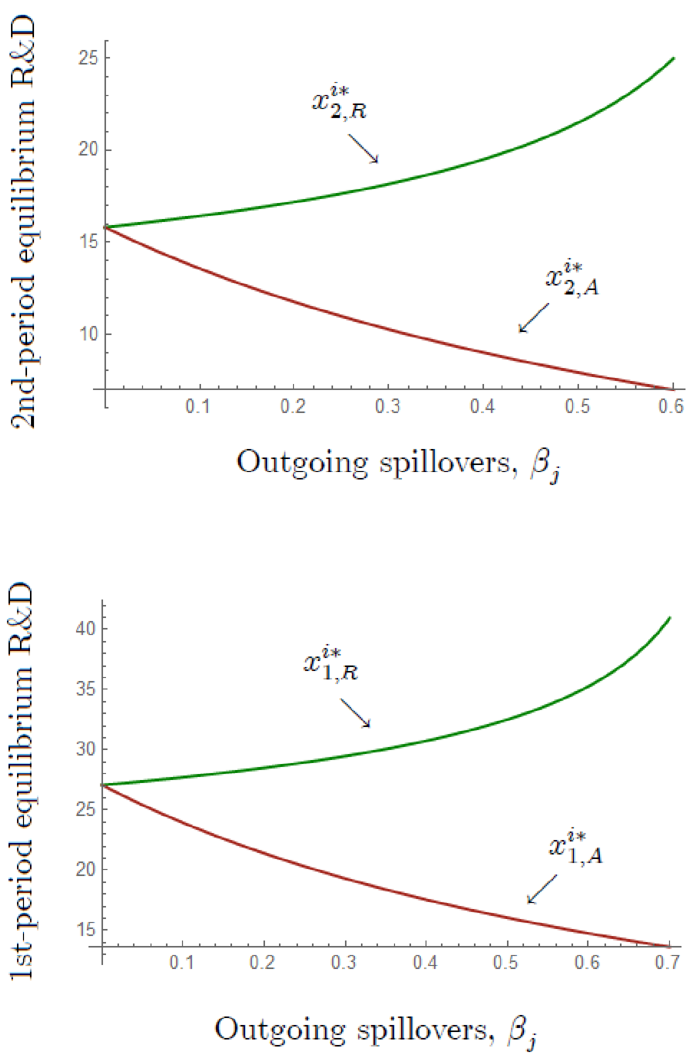

Figure 2 shows how firm i's equilibrium R&D incentives in both periods change with outgoing spillovers, β_j, in the RF and AJ models when $\beta_i = 0.6$, $a = 100$, $\bar{c} = 45$, and $k = 4$.

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. In period 1, firm i's marginal cost is $c_1^i = \bar{c} - f\left(x_1^i\right)$, while in period 2, its cost is

$$c_2^i = \bar{c} - f\left(y_2^i\right), \text{ where } y_2^i = x_1^i + x_2^i + \beta_i x_2^j. \tag{12}$$

The R&D production function f is assumed to be concave. As in the AJ model, only 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. Thus, outgoing spillovers only harm the innovative firm, making this firm to invest less in R&D.

4.2 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 (RJVs) or non-cooperative R&D investments yield more welfare, while firms engage in Cournot competition in the product market. RJVs internalize the knowledge externality and eliminate the duplication of costs of conducting R&D. In period 2, the RJV decides the levels of R&D, x_2^i and x_2^j, which maximize the joint profit,

$$\pi_2^{RJV} = \pi_2^i + \pi_2^j = \left(q_2^i\right)^2 - g\left(x_2^i\right) + \left(q_2^j\right)^2 - g\left(x_2^j\right), \tag{13}$$

where q_2^i and q_2^j are given by equation (4). In period 1, the RJV needs also to consider how the current R&D levels will affect the next period's cost reduction and R&D choices.

For large spillover rates 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 a competitive firm's R&D on its own profit, an RJV member also considers the *cross-profit* effect: firm i's R&D also affects firm j's profit, $\frac{\partial \pi_2^j}{\partial x_2^i} = \frac{2\left(2\beta_j - 1\right)}{3\left(1-\beta_i\beta_j\right)} q_2^j$.[16] When $\beta_j > \frac{1}{2}$, 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, in comparison, RJV firms invest more in R&D. 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

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

innovate more itself, because it can now internalize the benefits of its own R&D which is spilled over to another RJV member.

Social welfare is the unweighted sum of both firms' profits and the consumer surplus. In period 2, the consumer surplus is $U(q_2^i, q_2^j) - p_2^i q_2^i - p_2^j q_2^j$, implying the welfare function

$$U(q_2^i, q_2^j) - c_2^i q_2^i - c_2^j q_2^j - g(x_2^i) - g(x_2^j).$$

Here, we count the own-action effects on a firm's own net profit, the cross-profit effect as well as the increase in the consumer surplus. The social gains from the R&D activity are twofold: (a) R&D reduces the inefficiencies in production, allowing firms to produce at a more efficient scale; (b) the consumer-surplus increases: R&D allows a firm to produce more output and sell it at 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 that spirit, the RF model outlines and suggests interesting market implications regarding the degree of IP protection or antitrust laws. In industries in which innovation is a "building block", as in the RF model, the IP law must be such that it facilitates communication and knowledge diffusion, allowing for large knowledge spillovers that make firms' R&D decisions strategic complements. A welfare improving policy will be firms to be motivated to form RJVs.

4.3 Endogenous spillovers

Suppose that firms 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. However, we argue that in the RF model, the opposite holds when the innovator's R&D best-response curve is upward sloping.

Proposition 3 (Endogenous spillovers & R&D) *In industries with RF mechanisms, if a firm's R&D decision is a strategic complement, it chooses to disclose its knowledge to its product market competitor.*

As in Poyago-Theotoky (1999), suppose that once firms have made their R&D decisions, before they compete for consumers in the product market, they decide how much of the acquired knowledge to disclose. Firm i chooses β_j to maximize $\Pi_2^i = (q_2^i)^2$, where q_2^i is given in equation (3). When $\beta_i > \frac{1}{2}$, the second derivative $\frac{\partial^2 \Pi_2^i}{\partial \beta_j^2}$ is positive, indicating that there are corner solutions. In the RF model, a firm's production increases with outgoing spillovers, $\frac{\partial q_{2,R}^i}{\partial \beta_j} = \frac{2\beta_i - 1}{3(1-\beta_i\beta_j)^2}\left[x_1^i + x_2^i + \beta_i\left(x_1^j + x_2^j\right)\right] > 0$, when its R&D decision is a strategic complement, implying that the firm's profit-maximizing choice is information disclosure.[17] This result illustrates that with RF mechanisms, information disclosure between firms can create a form of R&D cooperation. R&D rivals will benefit by exchanging their research results and will desire to form cooperative R&D agreements such as RJVs, which are also welfare improving.[18] Note that in AJ model, Poyago-Theotoky (1999) also shows that we need to consider corner solutions but the profit maximizing choice is $\beta_j = 0$. In AJ model, innovators will never disclose any of their information when they compete in R&D, because a firm's production decreases with outgoing spillovers; $\frac{\partial q_{2,A}^i}{\partial \beta_j} = -\frac{x_2^i}{3} < 0$ for all β_i and β_j.[19]

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 the feedback is regenerative. Due to spillovers, a firm can exploit the knowledge acquired through its own and its rival's research, and build on it. We argue that when a firm's R&D best-response curve is upward sloping, outgoing spillovers can spur R&D, achieving greater efficiency enhancement. 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 happens because the firm can internalize a share of

[17] Firm i will choose $\overline{\beta}_i$.

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

[19] An alternative view would incorporate an absorptive capacity channel, as in Kamien & Zang (2000), where 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 outgoing spillovers are generated because the information provided is not useful, and thus the firm's absorptive capacity is also limited. At the other extreme, a firm's R&D approach can be basic which generates spillovers. A firm also cannot realize benefits from spillovers from its rival's R&D without engaging in R&D itself. Suppose that in the RF model, firms have formed an RJV and their R&D decisions are strategic complements. Then, they will choose broad R&D approaches to generate spillovers.

the provided benefit with incoming spillovers. In contrast to the existing literature on exogenous spillovers, we show that spillovers spur R&D even in markets with homogeneous products. If firms can choose the level of knowledge spillovers they create, we show that a firm will disclose its knowledge to its product market competitor. One could extend this analysis by examining the benefits of firms acting as leaders or followers in a sequential-move games as in Amir, Amir & Jin (2000), in the presence of RF mechanisms.

The empirical literature supports the idea that the development of knowledge-driven industries and technological parks such as Silicon Valley exploits regenerative feedback mechanisms. In "learning" regions and industries in which innovation is rushed, knowledge is defused during the innovation process. 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 (1988) and Kamien, Muller & Zang (1992), where 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 in industries due to different mechanisms of knowledge diffusion. R&D policies may also affect innovative firms' decision to enter or exit an industry as well as the financing of R&D. Boyarchenko & Chiang (2019) consider an industry of many small price taking firms subject to idiosyncratic productivity shocks, in which firms enter taking on debt. They show that in a competitive equilibrium, some firms exit and pay out their debt while others choose to default. When firms' R&D decisions are strategic complements, the presence of RF mechanisms may make exit or default decisions less desired. R&D policies and future research on firm strategies need 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 weaken intellectual property rights protections or even encourage exchange of ideas will allow innovators to seize additional knowledge and achieve better R&D outcomes. Policy makers must build an environment consisting of individuals and institutions who intend 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 Proposition 1

Firm j's first-order condition of second period profit is

$$\frac{2\gamma_j}{9}\left[a-\bar{c}+\gamma_j\left(x_1^j+x_2^j\right)+\frac{2\beta_j-1}{1-\beta_i\beta_j}\left(x_1^i+x_2^i\right)\right]-g'(x_2^j)=0.$$

We totally differentiate both firms' first-order conditions with respect to β_j. Equation (9) shows the decomposition of firm i's R&D incentives, while the decomposition of firm j's R&D incentives gives

$$\frac{2\gamma_j}{9\left(1-\beta_i\beta_j\right)}\left[3\beta_i q_{2,R}^{j*}+\gamma_j\left(\beta_i\sum_{t=1}^{2}x_{t,R}^{j*}+\sum_{t=1}^{2}x_{t,R}^{i*}\right)+\left(2\beta_j-1\right)\frac{dx_{2,R}^{i*}}{d\beta_j}\right]+\delta_{j,R}\frac{dx_{2,R}^{j*}}{d\beta_j}=0. \quad (14)$$

By equations (9) and (14), we get

$$\frac{dx_{2,R}^{i*}}{d\beta_j}=\frac{2\left(2\beta_i-1\right)\Psi_i}{9\left(1-\beta_i\beta_j\right)^2\Delta_2},$$

where

$$\Psi_i\equiv\frac{2\gamma_i\gamma_j}{3}\beta_i q_{2,R}^{j*}+\left(\frac{2\gamma_j^2}{9}-\delta_{j,R}\right)\gamma_i\left(\sum_{t=1}^{2}x_{t,R}^{i*}+\beta_i\sum_{t=1}^{2}x_{t,R}^{j*}\right)-3\delta_{j,R}q_{2,R}^{i*}.$$

Assumptions $(R.1)$ and $(R.2)$ guarantee that $\Delta_2>0$ and $\delta_{j,R}<0$. Hence, we have $\Psi_i>0$, implying $\frac{dx_{2,R}^{i*}}{d\beta_j}>0$, if and only if $\beta_i>\frac{1}{2}$ for all β_j, as stated in Proposition 1.

A.2 Proof of Proposition 2

In AJ model, each firm i maximizes the second-period profit function

$$\pi_2^i = \frac{1}{9}\left[a - \overline{c} + 2x_1^i + \left(2-\beta_j\right)x_2^i - x_1^j + \left(2\beta_i - 1\right)x_2^j\right]^2 - g\left(x_2^i\right),$$

and its first order condition yields

$$\frac{2}{9}\left(2-\beta_j\right)\left[a - \overline{c} + 2x_1^i + \left(2-\beta_j\right)x_2^i - x_1^j + \left(2\beta_i - 1\right)x_2^j\right] - g'\left(x_2^i\right) = 0.$$

Equation (11) shows the decomposition of firm i's R&D incentives, while the decomposition of firm j's R&D incentives with respect to β_j gives

$$\frac{2}{9}\left(2-\beta_i\right)\left[2x_{2,A}^{i*} + \left(2\beta_j - 1\right)\frac{dx_{2,R}^{i*}}{d\beta_j}\right] + \delta_{j,A}\frac{dx_{2,A}^{j*}}{d\beta_j} = 0. \tag{15}$$

We solve the equations (11) and (15), and get

$$\frac{dx_{2,A}^{i*}}{d\beta_j} = \frac{2}{3\Gamma_A}\left[\frac{\left(2-\beta_j\right)x_{2,A}^{i*}}{3}\left[\frac{4}{9}\ \left(2\beta_i - 1\right)\left(2-\beta_i\right) + \delta_{j,A}\right] + \delta_{j,A}q_{2,A}^{i*}\right], \tag{16}$$

where $\delta_{j,A} \equiv \frac{4}{9}\left(2-\beta_i\right)^2 - k$ and $\Gamma_A \equiv \delta_{i,A}\delta_{j,A} - \frac{4}{81}\left(2-\beta_i\right)\left(2-\beta_j\right)\left(2\beta_i - 1\right)\left(2\beta_j - 1\right)$. The stability conditions in the AJ model require $\delta_{j,A} < 0$ for any i, j and $\Gamma_A > 0$. To keep things simple, we assume $g\left(x_t^i\right) = \frac{k}{2}\left(x_t^i\right)^2$. When $\beta_i < \frac{1}{2}$, the derivative in (16) is clearly negative. To verify that this holds even when $\beta_i > \frac{1}{2}$, we substitute $\delta_{j,A}$ and $q_{2,A}^{i*} = \frac{3k}{2\left(2-\beta_j\right)}x_{2,A}^{i*}$ in (16) and get

$$\frac{dx_{2,A}^{i*}}{d\beta_j} = \frac{2}{3\Gamma_A}\left[\frac{2-\beta_j}{3}\left(\frac{4}{9}\ \left(2-\beta_i\right)\left(1+\beta_i\right) - k\right) + \left(\frac{4}{9}\left(2-\beta_i\right)^2 - k\right)\frac{3k}{2\left(2-\beta_j\right)}\right]x_{2,A}^{i*}.$$

The term in the brackets is negative for all β_i and β_j. Thus, we have $\frac{dx_{2,A}^{i*}}{d\beta_j} < 0$ for all β_i and β_j as stated in Proposition 2.