FIRM HETEROGENEITY, IMITATION, AND THE INCENTIVES FOR COST REDUCING R&D EFFORT[*]

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I develop and test a model of strategic R&D investments where innovating and non-innovating firms compete on the basis of their ability to reduce costs and imitate rivals. I find that a larger proportion of non-innovating rivals stimulates cost-reducing investments and attenuates the disincentive effect of imitation by innovators on firm level R&D. Key model properties are verified by estimating the first order condition for the optimal choice of R&D, using the 1994 Carnegie Mellon survey of U.S. industrial R&D. Results also suggest that R&D and size are simultaneously determined, with R&D being proportional to size, as predicted by the theoretical model.

I. INTRODUCTION

NEW SCIENTIFIC OR TECHNOLOGICAL KNOWLEDGE may involuntarily spill out and turn out to be of use in someone else's R&D effort, thus undermining the incentives to innovate (e.g., Arrow [1962] and Spence [1984]). Although the existence and large magnitude of R&D spillovers has been documented by a significant number of empirical studies, there is no empirical consensus as to whether R&D spillovers actually lower incentives (e.g., Griliches [1995], Cohen [1995]). Scholars have thus uncovered effects that might attenuate such a disincentive effect (e.g., Levin and Reiss [1988], Cohen and Levinthal [1989], De Bondt, Slaets and Cassiman [1992]). In particular, the work of Cohen and Levinthal [1989] suggests that in order to benefit from spillovers, a firm needs to undertake its own R&D activity, thus providing an explanation for a positive incentive effect of larger spillovers between innovators, in a given industry, on firms' R&D. In this paper, I present another conditioning factor of the relationship between spillovers and the incentives to innovate, suggesting that larger spillovers may stimulate a firm's R&D effort in industries where innovative capabilities are asymmetrically distributed across rivals.

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Indeed, one relatively unexplored aspect of the relationship between R&D and spillovers is the role of firm heterogeneity, which is an empirical regularity with respect to innovative activity. Cohen and Klepper [1992], for example, show that the distributions of firms' R&D intensities within industries tend to be uni-modal, positively skewed, with a long tail to the right and to include a large number of non-performers. What are the implications of such asymmetries on the relationship between spillovers and the incentives to innovate? Consistent with the absorptive capacity literature, one would expect, for example, that the non-innovating firms were less capable of imitating innovations introduced by other firms.[1] In the case of cost reducing R&D, imitators benefit from cost reductions and market share increases relative to the non-imitators, and thus the volume of output over which to spread the fixed costs of own R&D. The larger the number of firms that cannot imitate, or that benefit less from spillovers, the larger will be the market share increase due to imitation, and thus the positive cost-spreading effect on own R&D incentives.

The objective of this article is to formally analyze and test the implications of such an asymmetric market structure in order better to understand the impact of spillovers on the incentives to innovate by extending previous oligopoly models with identical firms, marginal cost reducing R&D and spillovers (e.g., d'Aspremont and Jacquemin [1988], De Bondt, Slaets and Cassiman [1992], Ziss [1994], Leahy and Neary [1997]). I model the strategic interaction between two types of firms: innovating firms, which invest in strategic cost reducing R&D, and the non-innovating firms – the fringe – competing in a homogeneous product market. I also assume that innovators are relatively more capable of imitating the innovating rivals' marginal cost reductions.

Key theoretical predictions of the model are that spillovers between innovating firms may stimulate a firm's R&D, provided that the relative number of non-innovating firms is sufficiently large, R&D costs sufficiently low, and demand is sufficiently elastic. Entry of a non-innovating firm may also stimulate a firm's R&D in industries with many innovators and large spillovers across them, but with small spillovers benefiting the fringe.

The comparative statics results related to the effect of spillovers and rivalry on the equilibrium level of R&D effort depend on the level and combinations of parameters that I cannot measure, such as, for example, the efficiency of R&D and the elasticity of demand. I can test, however, some of the unambiguous properties of the model using the 1994 Carnegie Mellon survey of industrial R&D in the United States (Cohen, Nelson, and Walsh [2000]). In particular, a central finding of the empirical analysis is that,

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[1] There is indeed empirical evidence that R&D performers are more likely to be successful in absorbing knowledge generated outside their R&D labs (e.g., Mowery [1983], Cohen and Levinthal [1989]).

holding an R&D investing firm's scale constant, a relatively larger number of competing fringe firms tend to increase their cost reducing R&D effort both directly and by dampening the disincentive effect due to outgoing spillovers benefiting other competing innovators, as predicted by the comparative statics properties of the theoretical model.

The paper is organized as follows. Section II outlines the model and presents the key comparative statics properties and results on the effect of spillovers and entry on firms' R&D effort. Section III describes the data, the econometric specification and the empirical analysis. A brief conclusion follows.

II. MODEL AND COMPARATIVE STATICS

In this section, I present the comparative statics analysis of a two-stage model where, in stage one, the innovating firms choose the amount of cost reducing R&D (R_j), with $j = 1, \ldots, N_n$, the cost of which is quadratic in R_j, and in stage two, these firms and N_f additional non-innovating firms, the fringe, compete à la Cournot in a homogeneous product market with linear demand, with subscript n referring to innovating firms and f to fringe firms. Marginal costs are equal to $c_i = c - \theta_f \sum_{j=1}^{N_n} R_j$ for a non-innovating firm i, and $c_j = c - R_j - \theta_n \sum_{z=1}^{N_n-1} R_z$, (with $z \neq j$), for an innovating firm j, with θ_f and θ_n representing the fraction of spillovers captured by fringe and innovating firms, respectively, and $0 \leqslant \theta_f < \theta_n \leqslant 1$. Details on assumptions, equilibrium values and stability conditions can be found in Appendix A.

The effect of spillovers and rivalry can be analyzed from the first order condition for the firm's choice of the optimal level of R&D of the first stage of the game:

$$(1) \qquad R_j = \frac{2b}{k} q_j^c \frac{\partial q_j^c}{\partial R_j},$$

with $b > 0$ inversely related to the elasticity of demand, $k > 0$ representing the R&D cost parameter (see Appendix). q_j^c represents the second stage output solution of an innovating firm (superscript c refers to Cournot equilibrium levels and subscript j to the jth innovating firm) and $\partial q_j^c \backslash \partial R_j$ represents its partial derivative with respect to own R&D effort:

$$(2) \qquad q_j^c = \frac{1}{b(N_f + N_n + 1)} \left[a - c_j + \sum_{i=1}^{N_f} (c_i - c_j) + \sum_{z=1}^{N_n-1} (c_z - c_j) \right], \text{ with } z \neq j;$$

$$(3) \qquad \frac{\partial q_j^c}{\partial R_j} = \frac{1 + N_f(1 - \theta_f) + (N_n - 1)(1 - \theta_n)}{b(N_f + N_n + 1)}.$$

Components (2) and (3) represent the two main drivers of R&D incentives in this model. In particular, the dependence of R&D efforts on component (2),

which I label the *scale effect*, indicates that incentives to innovate are higher if the cost reduction induced by R&D investments is applied to more units of output. Notice from (2) that a firm's output is higher the lower its marginal costs and the larger the differences between the marginal costs of each of its $N_f + N_n - 1$ rivals and its own marginal costs, that is its cost-based competitive advantage.

Component (3), which I label the output *expansion effect*, refers to the increase in profits resulting from the expansion of the investing firm's output. Such effect critically depends on the extent to which R&D reduces own costs and rivals' costs, via spillovers. In particular, additional R&D by firm *j* will stimulate the expansion of its output by reducing its marginal costs and by increasing its cost-based competitive advantage relative to innovating and non-innovating rivals.[2]

In what follows, I first analyze in detail the determinants of both components of R&D incentives, (2) and (3), focusing on spillovers and the number of rivals. Then, I present two propositions related to the net effect of key parameters on the equilibrium level of a firm's R&D effort.

Lemma 1   (impact of spillovers and rivalry on the *scale effect*):

Define the *scale effect* as the term q_j^c presented in (2). Then,

(i)   Larger spillovers benefiting the fringe firms will always decrease the *scale effect*;
(ii)   Larger spillovers between innovating firms will always increase the *scale effect*;
(iii)   Entry of a fringe firm will always decrease the *scale effect*.

Proof.   See Appendix B.

The intuition behind Lemma 1 is as follows. Larger spillovers from innovating to fringe firms (θ_f) will reduce the marginal costs of the latter,

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[2] More specifically, an increase in R&D by firm *j*, holding constant the R&D of the remaining innovating firms, will stimulate the expansion of firm *j* output mainly through three channels: a) by reducing own marginal costs by one unit, which accounts for the initial '1' in the numerator of (3); b) by increasing the cost difference relative to the fringe firms by $1 - \theta_f > 0$, due to the unit decrease in own marginal costs and a θ_f decrease of each of the N_f rival fringe firms' marginal costs; this effect accounts for the $N_f(1 - \theta_f)$ term in (3); c) by increasing the cost asymmetry relative to the other innovating rivals by $1 - \theta_n \geqslant 0$, which accounts for the $(N_n - 1)(1 - \theta_n)$ term in (3). Also note that the spillover parameters affecting the output *expansion effect* (3), by capturing the impact of own R&D on rivals' marginal costs, reflect outgoing R&D spillovers benefiting rivals. Output, instead, depends on both incoming spillovers (represented by the θ_n parameter affecting firm *j* marginal costs) and outgoing R&D spillovers (represented by the θ_f and θ_n parameters affecting firm *j* non innovating and innovating rivals, respectively). Although I do not allow the incoming and outgoing spillovers parameters benefiting the *j* innovating firm and its innovating rivals to be different in the theoretical model, the distinction is important for the empirical measurement of spillovers determining *output* and *expansion effects*, as further explained below in the empirical section.

increase their output at the expense of the investing firm and thus reduce, for any given level of R&D, the *scale effect* (Lemma 1-i). An increase in spillovers between innovating firms (θ_n) will reduce the marginal costs of innovating firms and increase their output and market share relative to the fringe firms, for any given level of R&D, thus increasing the *scale effect* (Lemma 1-ii). Entry of a fringe firm will decrease, for any given level of R&D, the residual demand faced by the investing firm, and thus reduce the *scale effect* (Lemma 1-iii).[3]

Lemma 2   (impact of spillovers and rivalry on the output *expansion effect* of additional R&D): Define the *expansion effect* as the term $\partial q_j^c \backslash \partial R_j$ presented in (3). Then,

(i)   Larger spillovers benefiting the fringe firms will always decrease the *expansion effect*;
(ii)   Larger spillovers between innovating firms will always decrease the *expansion effect*;
(iii)   Entry of a fringe firm will increase the *expansion effect* when spillovers benefiting the fringe firms are small;
(iv)   A larger number of fringe firms relative to the innovating firms will always increase the *expansion effect*;
(v)   A larger number of fringe firms relative to the innovating firms will always attenuate the negative impact of larger spillover between innovating firms on the *expansion effect*.

Proof: See Appendix B.

The intuition behind Lemma 2 is as follows. Larger spillovers benefiting the fringe firms (θ_f) or larger spillovers between innovating firms (θ_n) will reduce the output *expansion effect* of additional R&D by increasing the amount of outgoing spillovers benefiting the investing firm's rivals, thus reducing their marginal costs and the cost asymmetries induced by additional R&D (Lemmas 2-i and 2-ii). Entry of a fringe firm represents an additional competitor against which firm j can increase its competitive advantage through additional cost reducing R&D, thus stimulating the *expansion effect*,

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[3] The impact of entry of an innovating firm on the *scale effect* is not formalized, given its ambiguity. Intuitively, entry of a firm that produces the same level of R&D as the existing innovating firms, and does not result in the innovating firms adjusting their R&D, will have two offsetting effects on the *scale effect*. First, it will increase the collective output of the rivals of any one innovating firm, which will induce the latter to lower output, thereby reducing the *scale effect*. Second, it will reduce, the marginal costs of the investing firm, because of the R&D spillovers going from the innovating entrant and the jth investing firm, which will induce the latter to expand output, thereby increasing the *scale effect*. In some cases, such as that of perfect spillovers between innovating firms and sufficiently low R&D costs, the second effect may dominate, thereby implying that the entry of an innovator will increase output for each innovating firm, and therefore the *scale effect*.

provided the spillovers between innovating and fringe firms are sufficiently small (Lemma 2-iii). A relatively larger number of fringe firms will always increase the *expansion effect*, because it will reflect an industry populated by a relatively larger number of rivals with lower free-riding capabilities ($\theta_f < \theta_n$), thus increasing the positive effect that additional cost reducing R&D has on the firm competitive advantage (Lemma 2-iv).[4] An increase in the relative number of fringe firms will attenuate the negative impact of larger spillovers between innovating firms on the *expansion effect*, simply because of the relatively smaller number of free-riding innovating firms (Lemma 2-v).[5]

The analyzed properties of the model lead to the following two propositions, related to the effect of spillovers between innovating firms (θ_n) and entry of a fringe firm on the equilibrium level of R&D.[6]

Proposition 1: Larger spillovers between innovating firms will stimulate a firm's equilibrium level of R&D effort when the number of fringe firms relative to the innovating firms is sufficiently large, R&D costs are sufficiently low, and demand is sufficiently elastic.

Proof. See Appendix B.

The intuition behind this result can be obtained by using the previous lemmas. Larger spillovers between innovating firms (θ_n) will have an ambiguous effect on firms' incentives to invest in cost reducing R&D because larger θ_n will increase the *scale effect*, but will decrease the output *expansion effect* of additional R&D, as it follows from Lemmas 1-ii and 2-ii. When the relative number of fringe firms is high, the negative impact of larger outgoing spillovers benefiting other innovating rivals on the *expansion effect* will be smaller, as indicated by Lemma 2-v. An elastic demand will also be associated with a higher output *expansion effect*, whereas low R&D costs will be associated with low marginal costs of R&D effort. Under such conditions, the increased *scale effect*, due to larger spillovers between innovating firms, may offset the reduced *expansion effect*, with a net positive effect on the equilibrium level of a firm's R&D.

Proposition 2: Entry of a fringe firm will stimulate a firm's equilibrium level of R&D effort when the spillovers benefiting the fringe firms are sufficiently

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[4] Additional R&D increases the cost-based competitive advantage relative to the N_f fringe firms by $1 - \theta_f$, and by $1 - \theta_n$ relative to the $N_n - 1$ innovating rivals, with $1 - \theta_f > 1 - \theta_n$. An increase in the relative number of fringe firms increases the relative number of firms against which R&D has a larger positive impact in term of cost differences.

[5] Put differently, the positive effect that an increase in the relative number of fringe firms has on the *expansion effect*—just highlighted by the previous Lemma 2-iv—will always increase with larger spillovers between innovating firms, because it will increase the cost asymmetries induced by additional R&D.

[6] The derivation of the equilibrium level of R&D is presented in Appendix A, equation (4-A).

small, the industry is populated by a sufficiently large number of innovating firms, and the spillovers between innovating firms are sufficiently large.

Proof. See Appendix B.

Admittedly, proposition 2 is not particularly intuitive. It does, however show that parameter values exist such that entry of a fringe firm can stimulate the equilibrium level of R&D effort. The result arises because entry of a fringe firm has an ambiguous effect on R&D incentives since, although it would reduce the *scale effect*, it might also increase the *expansion effect* of R&D, provided that spillovers to the fringe firms are small, as follows from Lemmas 1-iii and 2-iii. Proposition 2 indicates that the net effect is positive when θ_f is small and θ_n and N_n are also large. The basic intuition is that on the one hand, small spillovers to the fringe firms assure a positive effect of the entry of a fringe firm on the *expansion effect*. On the other hand, a large number of innovating firms with large spillovers between them is associated with large aggregate spillovers benefiting the R&D investing firm (incoming R&D spillovers), low marginal costs and large output, which translates into low output for the fringe firms. Under such conditions, the entry of a fringe firm that produces the same level of output as the existing fringe firms will decrease the *scale effect* by a relatively lower amount. As a net result, for sufficiently small θ_f, large θ_n and large N_n, the increased *expansion effect* of R&D, due to the entry of a fringe firm, may offset the reduced *scale effect*, thus stimulating the equilibrium level of each innovating firm's R&D effort.

III.   EMPIRICAL ANALYSIS

Despite the ambiguity of the net effect of spillovers and rivalry on the equilibrium level of firm R&D investments, and the fact that the main comparative statics results depend on combinations of parameters that I cannot measure, I will test in this section some of the unambiguous properties of the model using the first order condition for the optimal choice of an innovating firm's R&D effort.

In particular, to obtain a tractable empirical specification, I multiply and divide the *expansion effect* (3) by b, the slope of the inverse demand function, take the log of both sides of the FOC (1), and obtain $\ln R_j = \ln (2/k) + \ln q_j^c + y$, where $y = \ln((\partial q_j^c \backslash \partial R_j)b) = g(\theta_f, \theta_n, N_f, N_n)$, and g is a non-linear function of the spillovers and rivalry parameters. I then approximate y with a second order polynomial approximation, using measures for outgoing spillovers (SPILLOUT), number of fringe firms (FRINGE), number of innovating firms (INNOVATORS), their squares and cross-products, plus an additive unobserved firm specific error term, ε. To simplify notation I omit the subscript j referring to the jth R&D performer, and obtain:

$$\ln R = \beta_0 + \beta_1 \ln \text{OUTPUT} + \beta_2 \text{FRINGE} + \beta_3 \text{INNOVATORS}$$
$$+ \beta_4 \text{SPILLOUT} + \beta_5 (\text{FRINGE} \times \text{SPILLOUT})$$
$$(4)$$
$$+ \beta_6 (\text{INNOVATORS} \times \text{SPILLOUT}) + \beta_7 \text{FRINGE}^2$$
$$+ \beta_8 \text{INNOVATORS}^2 + \beta_9 \text{SPILLOUT}^2 + \varepsilon.$$

By including a measure of output on the right-hand side of equation (4) I can thus control for the *scale effect* and test the separate effect of spillovers and asymmetric market structure on one of the components driving the incentives to introduce cost reducing innovations, the output *expansion effect* of additional R&D effort, presented in Lemma 2.

The empirical specification differs from the theoretical model in the following ways. Although the spillovers and rivalry parameters do not vary across innovators in the model, and thus the *expansion effect* is common to all innovating firms within the industry, I will use firm specific measures of outgoing spillovers (SPILLOUT) for a representative sample of U.S. R&D performers, which will provide relatively greater variance in estimating the model, as well as prevent imposing symmetry in the spillover variable affecting the marginal costs of the jth R&D performer (incoming spillovers) and those of its rivals (outgoing spillovers). Indeed, it is the latter type of spillovers which affects R&D incentives, once the *scale effect* is controlled for on the right hand side of (4). The *scale effect* is, rather, a function of both incoming and outgoing spillovers.[7] Note also that I do not separately include in the empirical specification (4) variables reflecting both spillovers to innovating and fringe firms because of the availability of a measure which reflects outgoing spillovers to all rivals, with implications to be discussed below.

The theory implies the following testable hypothesis:

H1. The elasticity of R&D with respect to output is unity ($\beta_1 = 1$), which directly follows from the FOC (1).
H2. The effect of larger SPILLOUT on firm R&D, holding output constant, is negative (according to Lemmas 2-i and 2-ii).[8]
H3. The marginal effect of FRINGE on R&D, holding output constant, is greater than the marginal effect of INNOVATORS (according to Lemma

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[7] As previously pointed out, output in (2) is affected by incoming spillovers through c_j and outgoing spillovers benefiting rivals through c_i and c_z.

[8] Indeed, an increase in spillovers to fringe firms (θ_f) or to innovating firms (θ_n) negatively affect firm R&D, holding output constant, by reducing the *expansion effect* (according to Lemmas 2-i and 2-ii) and it can be easily verified that a simultaneous change in both θ_f and θ_n, *ceteris paribus*, has also the same effect.

2-iv). Put differently, an increase in the relative number of fringe firms, holding output constant, stimulates R&D effort.[9]

H4. The cross-partial effect of FRINGE and SPILLOUT on R&D, holding output constant, is greater than the cross-partial effect of INNOVATORS and SPILLOUT (according to Lemma 2-v). Put differently, an increase in the relative number of fringe firms and SPILLOUT, holding output constant, stimulates R&D effort.

To perform the empirical analysis, I use cross-sectional data from the Carnegie Mellon survey (CMS) on industrial R&D. The population sampled is that of all R&D labs located in the U.S. conducting R&D in manufacturing industries as a part of a manufacturing firm.[10] The respondents were R&D lab managers who were asked to answer questions with reference to the 'focus industry' of their R&D unit, where the focus industry was defined as the principal industry for which the unit was conducting its R&D. The data refer to the 1991–93 period (see Cohen *et al.* [2000], for a more detailed description of the survey methodology and data).

In particular, the CMS contains cross-sectional measures for both cost reducing R&D investment and output, the endogenous, firm-specific variables of the model. The former is measured as the percentage of company-financed business unit R&D expenditures devoted to new or improved processes. The second is measured as the number of business unit employees. As a measure of SPILLOUT, I use a factor-based measure of the percentage of process innovations for which the strategies employed to protect the competitive advantage from those innovations (patents and other legal mechanisms, secrecy, lead times, complementary marketing and manufacturing capabilities, and process complexity) were not effective (see Appendix C). The main advantages of this variable are that it measures the benefits captured by a firm's rivals worldwide, which is the spillover variable affecting the *expansion effect* of R&D, and it is also specifically related to process innovations. The main disadvantage is that it does not allow one to distinguish between benefits captured by the fringe firms (θ_f) versus the innovating firms (θ_n). Interestingly, however, we can interpret some of the empirical results shown below as suggesting that spillovers to the fringe are small, mitigating this measurement problem. Note also that I experimented with different measures of outgoing spillovers, such as the maximum score

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[9] Note also that failure to reject such restriction implies that the spillovers captured by innovating firms are higher than those captured by the fringe firms, i.e. $\theta_n > \theta_f$, as it can be verified from the proof of Lemma 2-iv in Appendix B, so that the empirical specification actually allows the testing of such a model's assumption.

[10] The sample was randomly drawn from the eligible labs listed in the Directory of American Research and Technology (Bowker [1995]) or belonging to firms listed in Standard and Poor's Compustat, stratified by 3-digit SIC industries. Valid responses were received from 1,478 R&D units, with a response rate of 54%.

received by any one of the process innovation appropriability mechanisms for each respondent (cf. Cohen and Levinthal [1989]), and obtained similar results to those presented in this paper.

As a measure of the number of innovating firms, the survey contains the total number of worldwide competing innovators of the parent firm in the focus industry in which the R&D lab operates, denoted INNOVATORS in equation (4). The number of fringe firms is measured as the difference between the total number of worldwide competitors, also reported by the R&D managers, and the number of innovating firms, denoted FRINGE in equation (4).[11] I also include 18 dummies on the right-hand side of (4) constructed using 2/3-digit SIC groupings to control for unobserved industry level determinants of R&D incentives.[12]

Finally, a critical step in estimating (4) is to find instruments for the business unit employees variable, given the simultaneity between R&D and output implied by the theoretical model. The model suggests that measures associated with the size of the market would be correlated with the output of firm j, but not with the *expansion effect*, and thus not likely to be correlated with the error term of (4).[13] In particular, I use the natural logarithm of the value of *industry* shipment in 1992 and its rate of growth from 1987 to 1992, measured at the 4-digit SIC *industry* level as instruments for size.[14] I shall also test the validity of such instruments.

In the empirical analysis that follows, the unit of analysis is the business unit within a parent firm, operating in the focus industry of the responding R&D lab. For the analysis, I restricted the Carnegie Mellon survey sample to firms with business units of 10 or more employees and at least 5 respondents in their 2/3-digit SIC industry. After dropping observations with missing data for the variables of interest, I obtain a sample of 713 observations.[15]

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[11] Competing innovators are defined as those rivals able to introduce competing innovations in time to effectively diminish a firm's profits from its innovations. Note that both INNOVATORS and FRINGE vary across respondents because they represent each respondent's assessment of its focus industry conditions, often reflecting a particular niche or market segment.

[12] For example, the theory considers homogeneous good competition. The industry dummies could serve as a crude control for the unobserved degree of product differentiation. De Bondt, Slaets, and Cassiman [1992], among others, have indeed shown that the degree of product differentiation within the industry will condition the relationship between spillovers, number of rivals and cost reducing R&D.

[13] The positive quantity $a - c$, with a the intercept of the linear demand function and c the constant in the marginal cost function of both fringe firms and innovators, which is a measure of the size of the market, affects the *scale effect* (2), but not the *expansion effect* (3). That is, measures associated with the size of the market $a - c$ are all good instrumental variables for output in the R&D equation.

[14] Source: *1992 Census of Manufacturers*, U.S. Department of Commerce, Bureau of the Census.

[15] The sample also reflects a 1% symmetric trimming of the R&D and business unit size distributions.

TABLE I
DESCRIPTIVE STATISTICS
713 BUSINESS UNITS

	Mean	Median	Std Dev	Min	Max
Endogenous variables					
COST REDUCING R&D ($ millions)	7.7	0.6	27	0	270
EMPLOYEES (thousands)	3.1	0.5	7.2	.01	50
Exogenous variables					
FRINGE	19	8	35	0	350
INNOVATORS	10	5	20	0	400
SPILLOUT (Factor-based measure)	− 0.1	0.01	0.9	− 2.8	1.3
Instrumental variables					
INDUSTRY SALES ($ billions)	48.4	39.5	42.5	2.1	238.4
INDUSTRY SALES GROWTH (%)	4.8	4.3	3.3	− 9.9	13.8

Table I presents descriptive statistics for all the variables used in the empirical analysis, including the instruments. The average business unit has about $8 million in company financed process R&D and 3,000 business unit employees. As Table I suggests, respondents report, on average, 19 non-innovating competitors, about twice as many as innovating ones.

Estimates of equation (4) are presented in Table II, obtained using the general method of moments (GMM), including OLS estimates and two specifications, with and without interactions between the spillovers and rivalry measures and squared terms.

I find an elasticity of R&D with respect to business unit size (β_1) of 1.00 and 0.99 in the instrumented specifications (with and without interactions respectively), and 0.8 in the OLS cases. The test of the null hypothesis of an elasticity equal to unity (not shown) is rejected in the specifications estimated with OLS, whereas it is not rejected when instrumental variables are used, confirming hypothesis 1. The exogeneity of business unit size was indeed rejected at the 1% confidence level by a preliminary Durbin-Wu-Hausman test, confirming the need to use instrumental variables for estimation.[16] The instruments are individually, as well as jointly, significant in the first stage regressions, and a test of the over-identifying restrictions (not shown) implicit in their use supports the hypothesis that they are uncorrelated with the disturbances of the R&D equation.

The results indicate that the impact of SPILLOUT on the *expansion effect* is negative and significant across specifications and methods, supporting

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[16] In the preliminary instrumental variable regression explaining the log of business unit employees, *industry* sales growth and the natural logarithm of *industry* sales are significant at the 1% and 10% significance level, respectively. The two instruments are jointly significant at the 1% confidence level, and the R^2 from such preliminary regression is 0.14.

hypothesis 2.[17] The first order effect of a larger number of fringe firms on the *expansion effect* is positive, although not significantly different from zero.[18] This finding indirectly suggests that spillovers benefiting the fringe firms are low (as implied by Lemma 2-iii). The difference between the first order effects of FRINGE and INNOVATORS is positive across specifications and methods (although significant at conventional levels only for the specification without interactions estimated with GMM), consistent with the hypothesis that a higher ratio of fringe firms is associated with higher R&D, holding output constant, via an increased output *expansion effect*, and that spillovers between innovating firms are higher than those benefiting the fringe firms, as indicated in hypothesis 3.[19]

Finally, the above results indirectly suggest that spillovers benefiting the fringe firms are empirically low.[20] I can then interpret, with some caution, the interaction effects between SPILLOUT and FRINGE, and SPILLOUT and INNOVATORS as mainly reflecting interactions between spillovers between innovating firms and the number of fringe and innovating firms (coefficients β_5 and β_6 in equation (4)). From this perspective, the comparative statics properties would suggest that $\beta_5 - \beta_6 > 0$, as implied by Lemma 2-v. The empirical estimates contained at the bottom of Table II (PROPORTION OF FRINGE × SPILLOUT), which are greater than zero with 95% confidence level using both OLS and GMM, confirm such predictions. The latter finding suggests that industries with a relatively higher number of fringe firms and higher spillovers across innovating firms are characterized by higher incentives to innovate, holding everything else constant, confirming hypothesis 4. Put differently, a relatively larger number

[17] The marginal effect of SPILLOUT, reported at the bottom of Table II, is $(\beta_4 + \beta_5 \text{FRINGE} + \beta_6 \text{ INNOVATORS} + 2\beta_9 \text{SPILLOUT})$, which is computed at the mean of the sample. For the specification without interactions an estimate of the marginal effect is represented by the parameter β_4. Note that, in performing the empirical analysis, I also test for the potential endogeneity of SPILLOUT, which may be caused by the potential correlation between factors driving the effectiveness of the different appropriation mechanisms (captured by SPILLOUT) and other unobserved factors affecting R&D productivity, possibly reflected by the disturbance in the R&D equation. A Durbin-Wu-Hausman test, however, fails to reject the null hypothesis of exogeneity of SPILLOUT, using the same instruments employed for size plus the industry average of SPILLOUT at the level of the primary industry of the parent firm of the R&D lab, following Arora, Ceccagnoli, and Cohen [2003], who used the patent-related appropriation measure to analyze the relationship between R&D and patenting decisions.
[18] The marginal effect of FRINGE is computed as $(\beta_2 + \beta_5 \text{SPILLOUT} + 2\beta_7 \text{FRINGE})$ and is evaluated at the mean of the sample. For the specification without interactions, an estimate of the marginal effect is represented by the parameter β_2.
[19] The difference between the marginal effects of FRINGE and INNOVATORS, evaluated at the mean of the sample, is computed as $(\beta_2 - \beta_3 + (\beta_5 - \beta_6)\text{SPILLOUT} + 2\beta_7 \text{FRINGE} - 2\beta_8 \text{INNOVATORS})$. For the specification without interactions, an estimate of the effect is represented by the difference $\beta_2 - \beta_3$.
[20] The indirect finding that spillovers to fringe firms are low is consistent with the idea that firms without innovative capabilities possess relatively low imitation capabilities.

TABLE II
ESTIMATES

Parameter	Variable	OLS	GMM	OLS	GMM
β_0	Constant	− 6.737**	− 7.830**	− 6.563**	− 7.781**
		(0.305)	(1.582)	(0.312)	(1.605)
β_1	LOG OF B.U. EMPLOYEES	0.832**	0.989**	0.822**	0.997**
		(0.033)	(0.218)	(0.033)	(0.222)
β_2	FRINGE	0.001	0.001	0.004	0.003
		(0.002)	(0.002)	(0.004)	(0.004)
β_3	INNOVATORS	− 0.004	− 0.005[a]	− 0.001	− 0.004
		(0.003)	(0.003)	(0.006)	(0.007)
β_4	SPILLOUT	− 0.247**	− 0.263**	− 0.249**	− 0.267**
		(0.071)	(0.076)	(0.097)	(0.095)
β_5	FRINGE × SPILLOUT			0.002	0.002
				(0.002)	(0.002)
β_6	INNOVATORS × SPILLOUT			− 0.012*	− 0.011*
				(0.005)	(0.005)
β_7	FRINGE^2			− 1.0E-05	− 6.9E-06
				(1.7E-05)	(1.5E-05)
β_8	INNOVATORS^2			− 3.0E-05	− 2.0E-05
				(1.9E-05)	(1.7E-05)
β_9	SPILLOUT^2			− 0.173*	− 0.145[a]
				(0.069)	(0.077)
	Marginal effects				
FRINGE		0.001	0.001	0.003	0.002
		(0.002)	(0.002)	(0.003)	(0.003)
INNOVATORS		− 0.004	− 0.005[a]	− 0.001	− 0.004
		(0.003)	(0.003)	(0.005)	(0.006)
SPILLOUT		− 0.247**	− 0.263**	− 0.317**	− 0.321**
		(0.071)	(0.076)	(0.076)	(0.075)
PROPORTION OF FRINGE		0.006	0.006[a]	0.004	0.006
		(0.004)	(0.003)	(0.007)	(0.007)
PROPORTION OF FRINGE × SPILLOUT				0.013*	0.013*
				(0.006)	(0.005)

Notes:
1. Standard errors below estimates in parenthesis.**, *, [a]Significantly different than zero at the 0.01, 0.05, and 0.10 confidence levels.
2. A set of 18 industry dummies is included in all specifications (estimates are not shown).
3. The Number of observations used is 713. For the specifications estimated with OLS the R^2 is 0.53 (without interactions) and 0.54 (with interactions).

of technologically capable rivals tends to worsen the negative effect of spillovers on the incentives to innovate.

IV. CONCLUSION

This paper argues that when R&D and imitative capabilities are asymmetrically distributed across firms, exogenous changes in the extent of imitation across rivals' R&D may actually stimulate a firm's incentives to innovate. In particular, a key finding of the model is that a greater proportion of the market populated by non-innovating firms may stimulate the expansion of innovating firms' output as a result of larger incoming spillovers (thus providing a positive *scale effect* on R&D incentives) as well as dampen the disincentive effect of larger spillovers benefiting innovating

rivals' costs (outgoing cost reducing spillovers) on the output *expansion effect* of additional cost reducing R&D.

The data allow one to test only some of the comparative statics properties of the theoretical model. In particular, by estimating the first order condition of the optimal choice of R&D, I can test the impact of spillovers and rivalry on one component of the incentives driving innovation, the output *expansion effect* of additional R&D, which critically depends on the extent to which own R&D reduces own costs and rivals' costs—via spillovers. In particular, the empirical analysis confirms that a relatively higher number of fringe firms tend to increase R&D, holding business unit size constant, both directly and by attenuating the negative impact of outgoing spillovers on a firm's R&D effort. I also find that business unit size is endogenous, and that cost reducing R&D is proportional to business unit size, as predicted by the model, a fact that should be taken into consideration by scholars analyzing the empirical determinants of innovation incentives in the Schumpeterian tradition, who have neglected the simultaneity between size and R&D (cf. Cohen [1995]).

Among other limitations, the model only applies to industries with homogeneous product competition, with firms competing on quantities, and exogenous market structure.[21] The implications of a more general model, with more general demand and cost specifications, should be analyzed.[22] A more important limitation is that asymmetries are taken to be exogenous in

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[21] Attempts to generalize the model in order to consider an endogenous market structure, however, reveal that the comparative statics properties become quite intractable in the present setting. From a dynamic point of view, however, it would be desirable to endogenize the spillover parameter and the number of firms. In particular, the model suggests the possible existence of a positive self-reinforcing feedback cycle, whereby larger cost reducing spillover tend asymmetrically to benefit competitors because of their asymmetric R&D capabilities by stimulating output at the expense of less innovative firms, thus conferring yet greater incentives to invest in R&D due to the spreading of the R&D fixed costs over a larger volume of output. The greater firm R&D will also increase an innovating firm spillover absorption capacity, thus further stimulating own output at the expense of less innovative firms. The greater the proportion of the market populated by less innovative firms, the greater the positive incentives for R&D provided by spillovers, because of the easier expansion of innovating firms' output as a response to cost reducing spillovers. Arguably, as the more innovative firms expand over time, and fringe firms exit, as a response to larger asymmetric spillovers, we would expect this positive self-reinforcing effect of spillovers on R&D incentives to diminish.

[22] Amir [2000], for example, suggests that the modeling of spillovers as leakages in technological know-how that take place in final outcomes, rather than in R&D effort, as in the theoretical setting I use in this article, has some questionable implications, such as the perfect complementarity pattern in firms' R&D outcomes of independent R&D labs. Martin [2002] contains an explicit theoretical treatment of how spillovers in R&D effort versus final outcomes affect the incentives to innovate in the context of a racing game model. Note, finally, that the present model does not suggest that industries with a relatively high number of fringe firms should also be characterized by higher levels of total industry R&D. Indeed, the present paper's findings raise interesting, albeit unanswered questions, on what is the socially optimal level of industry heterogeneity in term of its relationship with spillovers and innovation incentives, which are left for future research.

the present setting, and it would be interesting to analyze the implications of a more dynamic model explaining the genesis of such heterogeneity.

In conclusion, although several limits are associated with the static theoretical framework presented and the underlying data and measures, the present paper contributes to explain why the relationship between spillovers and the incentives to innovate is so controversial, by finding yet another important neglected conditioning factor, namely the composition of the industry in terms of true innovating firms and the competitive fringe.

APPENDIX A

DERIVATION OF THE EQUILIBRIUM LEVEL OF OUTPUT AND R&D EFFORT.

In stage 1 of the game, the innovating firms choose the optimal amount of R&D, given the stage 2 product quantities. In stage 2, all the firms choose the optimal level of production, given the R&D level that results from stage 1. The game is solved using backward induction, i.e., by first solving the production stage, where profits are $(p - c_i)q_i$ for the ith fringe firm, with $i = 1, \ldots \ldots, N_f$, $(p - c_j)q_j$ for the jth innovating firm, with $j = 1, \ldots \ldots, N_n$, $N_n \geqslant 2$, and $p = a - bQ$, with $Q = \Sigma q_i + \Sigma q_j$, $a, b > 0$; $a - c > 0$. Marginal costs are equal to $c_j = c - R_j - \theta_n \sum_{z=1}^{N_n-1} R_z$, for the jth innovating firm, with $z \neq j$, $c_i = c - \theta_f \sum_{j=1}^{N_n} R_j$ for i^{th} fringe firm, and with $0 \leqslant \theta_f < \theta_n \leqslant 1$. Subscript n refers to innovating firms and f to fringe firms.

In stage 2, each firm maximizes profits by choosing output, given their competitors' output and the post-R&D marginal costs determined in stage 1. The first order conditions give a system of $N = N_f + N_n$ simultaneous equations, whose solutions represent the equilibrium level of output in stage 2:

$$(1\text{-A}) \qquad q_i^c = \frac{1}{bG} \left[a - c_i + \sum_{j=1}^{N_n} (c_j - c_i) + \sum_{l=1}^{N_f-1} (c_l - c_i) \right]$$

$$= \frac{1}{bG} \left(a - c - A \sum_{j=1}^{N_n} R_j \right), \text{ with } l \neq i;$$

$$(2\text{-A}) \qquad q_j^c = \frac{1}{bG} \left[a - c_j + \sum_{i=1}^{N_f} (c_i - c_j) + \sum_{z=1}^{N_n-1} (c_z - c_j) \right]$$

$$= \frac{1}{bG} \left(a - c + BR_j + D \sum_{z=1}^{N_n-1} R_z \right), \text{ with } z \neq j.$$

Superscript c indicates the *Cournot-Nash* equilibrium quantities in the product market, c_i and c_j are defined above and

$$(3\text{-A}) \qquad \begin{array}{ll} A \equiv N_n \theta_n - N_n \theta_f + 1 - \theta_f - \theta_n; & D \equiv N_f \theta_n - N_f \theta_f + 2\theta_n - 1; \\ B \equiv N_f + N_n - \theta_f N_f - \theta_n N_n + \theta_n; & G \equiv N_f + N_n + 1. \end{array}$$

In stage 1, only the innovating firms invest in R&D and the N_n objective functions for these firms are $\underset{R_j}{Max} \left[b(q_j^c)^2 - \frac{k}{2} R_j^2 \right]$, with q_j^c defined in (2-A), b is the slope of the inverse demand curve, $k > 0$ is an exogenous parameter reflecting the efficiency of R&D

activity, which is assumed to be characterized by diminishing returns. The N_n innovators maximize profits by choosing the optimal level of cost reducing R&D, given the R&D levels of their rivals. The stage 1 first order conditions give a system of N_n equations, whose solution represents a Nash equilibrium in R&D levels, obtained by assuming symmetry within the innovators' group:

$$(4\text{-}A) \qquad R = (a - c)B/S_2,$$

with $a - c > 0$ by assumption, $S_2 \equiv (kb/2)G^2 - B[B + (N_n - 1)D] > 0$ by stability, B, D, G defined in (3-A) [23].

APPENDIX B

PROOF OF LEMMA 1

(i) $\frac{\partial q_j^c}{\partial \theta_f} = -\frac{1}{bG} N_f \sum_{j=1}^{N_n} R_j < 0.$

(ii) $\frac{\partial q_j^c}{\partial \theta_n} = \frac{1}{bG}\left((N_f + 2) \sum_{z=1}^{N_n-1} R_z - (N_n - 1)R_j\right)$, with $z \neq j$,

which is positive when evaluated at the symmetric equilibrium level of R&D, whose positivity is implied by the R&D-stage stability conditions. It is easily verified that the partial derivative tends to increase as N_f gets large.

(iii) $\frac{\partial q_i^c}{\partial N_f} = -\frac{1}{G} q_i^c < 0$, with $G > 1$ defined in Appendix A (3-A), and $q_i^c > 0$ being the second-stage fringe firms' output solutions defined in Appendix A (1-A), assumed to be positive.

PROOF OF LEMMA 2

(i) $\frac{\partial^2 q_j^c}{\partial R_j \partial \theta_f} = -\frac{1}{bG} N_f < 0.$

(ii) $\frac{\partial^2 q_j^c}{\partial R_j \partial \theta_n} = -\frac{1}{bG}(N_n - 1) < 0.$

(iii) $\frac{\partial^2 q_j^c}{\partial R_j \partial N_f} = \frac{A}{bG^2}$, with A, defined in Appendix A (3-A), positive when θ_f is less than θ_f^*, with $\theta_f^* = \frac{1 + (N_n - 1)\theta_n}{N_n + 1}.$

(iv) $\frac{\partial^2 q_j^c}{\partial R_j \partial N_f} - \frac{\partial^2 q_j^c}{\partial R_j \partial N_n} = \frac{\theta_n - \theta_f}{bG} > 0$, with $\theta_n > \theta_f$ by assumption.

(v) $\frac{\partial^3 q_j^c}{\partial R_j \partial \theta_n \partial N_f} - \frac{\partial^3 q_j^c}{\partial R_j \partial \theta_n \partial N_n} = \frac{1}{bG} > 0.$

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[23] The first stage FOC is provided in the main text, equation (1). The first stage SOC for an optimum requires $B^2 - (kb/2)G^2 < 0$, whereas stability conditions for the N_n-firm symmetric equilibrium in the R&D game can be derived by noting that (see Dixit, 1986) $\frac{\partial^2 \pi_j}{\partial R_j \partial R_j} \pm (N_n - 1) \cdot \frac{\partial^2 \pi_j}{\partial R_j \partial R_z} < 0$, for $z \neq j$, that is $S_1 \equiv \frac{kb}{2}G^2 - B[B - (N_n - 1)D] > 0$, for $D < 0$, and $S_2 \equiv \frac{kb}{2}G^2 - B[B + (N_2 - 1)D] > 0$, for $D > 0$, with B, G, D defined in (3-A). Two stability conditions are needed because the sign of $\frac{\partial^2 \pi_j}{\partial R_j \partial R_z} = \frac{2BD}{bG^2}$, for $z \neq j$, is ambiguous (b, B, and G are positive, but the sign of D is ambiguous). Indeed, R&D investments are strategic substitutes (complements) when D is less (greater) than zero. The above conditions, together with the SOC, assure positive R&D, quantities and profits for the innovators in equilibrium. I further assume that $\frac{kb}{2} \geqslant \frac{\tilde{A}B}{G}$, with $\tilde{A} = N_n(\theta_n - \theta_f) + 1 - \theta_n$, to assure non-negative quantities and profits for the fringe firms in equilibrium. Stability in this model, with all firms producing positive quantities and profits, can basically always be achieved by setting k or b sufficiently high.

PROOF PROPOSITION 1

Sign $[\partial R/\partial \theta_n] = -$ Sign$[\Phi]$, with $\Phi = (kb/2)G^2 - (N_f+1)B^2$, with B and G defined in (3-A). I set k and b at their lowest level compatible with stability, i.e., $\frac{kb}{2} = \frac{B[B-(N_n-1)D]}{G^2} + \rho_1$ when $D < 0$, and $\frac{kb}{2} = \frac{B[B+(N_n-1)D]}{G^2} + \rho_2$ when $D > 0$, with D defined in (3-A) and ρ_1 and ρ_2 being two arbitrary small positive numbers. It is then easily verified that $N_f > N_n\text{-}1$ implies $\Phi < 0$, and thus $\partial R/\partial \theta_n > 0$.

PROOF OF PROPOSITION 2

$\partial R/\partial N_f = (b\psi)/S_2$, with $\psi = q_n^c A - q_f^c B$, with q_f^c and q_n^c being the second stage output solutions for the fringe firms and the innovating firms, given in (1-A) and (2-A), evaluated at the symmetric equilibrium level of R&D, A and B defined in (3-A). Since $b > 0$ and $S_2 > 0$ then $q_n^c > q_f^c$, while $A > B$, i.e., $N_f\,(1-\theta_f) - (N_n-1)(2\theta_n-1) + \theta_f(N_n+1) < 0$, is sufficient for $\partial R/\partial N_f > 0$, which is satisfied for sufficiently low θ_f, high θ_n and high N_n. In particular, note that $\theta_n > 1/2$ is necessary for $\partial R/\partial N_f > 0$. The condition implies that entry of a fringe firm can stimulate R&D effort for low ratios of N_f/N_n, as it can be verified by evaluating $A - B$ at $\theta_f = 0$ and $\theta_n = 1$, which reduces to $N_f < N_n - 1$.

APPENDIX C

FACTOR-BASED MEASURE OF PROCESS-RELATED OUTGOING SPILLOVERS (SPILLOUT)

To measure the benefits captured by a firm's rivals worldwide, which is the critical spillover variable affecting the *expansion effect* of R&D, I construct a factor-based measure of the percentage of process innovations for which a) 'Secrecy', b) 'Patent protection', c) 'Other legal mechanisms' (such as design registration or copyright), d) 'Being first to market', e) 'Complementary sales/service', f) 'Complementary manufacturing facilities and know-how', or g) 'Process complexity' were not effective in protecting the parent firm's competitive advantage from those process innovations in the 1991–1993 period. I then assign to each respondent the estimated factor score corresponding to the first extracted factor (labeled SPILLOUT in the empirical section of the paper), which accounts for the greatest amount of variance, representing a linear composite of the optimally weighted variables under analysis. Table III shows the factor loadings and the eigenvalue.

TABLE III
SPILLOUT: FACTOR LOADINGS

	Factor Loading
Variable	First Factor
Complementary manufacturing/know-how	0.66
Lead times	0.66
Complementary sales/service	0.66
Process complexity	0.63
Other legal	0.48
Secrecy	0.36
Patent protection	0.36
Eigenvalue	2.2

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