R&D, Knowledge Spillovers, and Competition among Firms with Asymmetric Technological Capabilities

Marco Ceccagnoli*
Ashish Arora
Wesley Cohen
William Vogt

July 1998

*: Corresponding author: H. John Heinz III School of Public Policy and Management, Carnegie Mellon University, 5000 Forbes Av., Pittsburgh, PA, 15213, USA; email: marcoc@andrew.cmu.edu; telephone: (412)268-8892; fax: (412)268-7036.

1. Introduction

Innovative firms are unable to fully appropriate the returns from their R&D investments. To the extent that the new knowledge associated with R&D involuntarily flows to competitors, the private incentives to further invest in R&D are diminished (Arrow 1962 and Spence 1984, among others,) a fact that is labeled "the disincentive effect of spillovers."

The existence and large magnitude of R&D spillovers has been documented by a significant number of empirical studies (Griliches, 1995.) There is also a growing body of evidence on inter-industry differences in spillovers and appropriability of returns from R&D, but there is no empirical consensus about whether R&D spillovers lower private R&D investments (Cohen, 1995.) Scholars have tried to theoretically rationalize the empirical puzzle by looking at factors that might reverse the "disincentive" prediction (Levin and Reiss, 1988, Cohen and Levinthal, 1989.) However, the standard "disincentive" models are still very influential from a public policy toward R&D perspective (Leahy and Neary, 1997.)

Even though much empirical work is still needed, a key theoretical aspect of this issue has not been considered. In particular, the existing literature has not adequately explored the role of asymmetries in market structure in affecting the relationship between knowledge spillovers and R&D investments.

The starting point of my analysis is based on an empirical regularity: the distributions of firms' R&D intensities (R&D over sales) within industries tend to be uni-modal, positively skewed, with a long tail to the right and include a large number of non-performers (Cohen and Klepper, 1992.) To the extent that R&D investments are fundamental determinants of the rate of technical change, the empirical regularity also implies that there are significant technological asymmetries among firms in each industry.

In this paper I present a model of R&D-based competition among asymmetric firms in oligopolistic industries that reflects the above empirical regularity by introducing two type of rival firms. Each industry is populated by N_1 R&D non-performers and N_2 R&D performers, characterized by different abilities or possibilities to benefit from the pool of knowledge spillovers generated by R&D activities. The model, that nests the standard symmetric oligopoly model with R&D investments and spillovers (D'Aspremont and Jacquemin,1998, and Kamien et al., 1992, among others,) yields interesting and counterintuitive results.

In particular, the analysis shows how differences in firms' innovative capabilities at generating technical change and absorbing knowledge spillovers from rivals will change standard theoretical predictions about the negative effect of spillovers and competition on firms' R&D investments. Indeed, one result of the comparative static is that under a wide range of values of the parameters, greater spillovers increase the equilibrium value of R&D investments, contrary to the prediction of symmetric oligopoly models that do not take into account innovation based cost asymmetries. It is, however, an increase of spillovers that benefits the R&D performing firms that may induce an increase in R&D investments. An increase of spillovers that benefits the fringe firms will always lead to lower R&D investments. These results are difficult to test empirically because there are not good measures or proxies for the spillover parameter of the fringe firms; whereas, the effect of larger spillovers among innovators on R&D levels is ambiguous.

A second result is that entry of new competitors in the industry has a substantially different effect on R&D, depending on the entrants' capabilities. An entrant with low capabilities at generating innovations and absorbing knowledge spillovers will get lower market shares and thus will provide a lower disincentive effect on R&D compared to a more capable innovator. The model indeed shows that the composition of the industry in term of innovators and fringe firms will have important effects on R&D incentives. The empirical analysis appears to be consistent with the theoretical prediction.

A third, and related result, is that industries where the number of innovators relative to the fringe firms is large will also be characterized by deeper appropriability problems, that is the negative disincentive effect of spillovers among innovators on R&D will be greater. Also in this case the empirical test is consistent with the theory.

The empirical analysis uses the 1994 Carnegie Mellon survey of industrial R&D in the United States (Cohen, Nelson, and Walsh, 1997). This survey provides measures for knowledge spillovers across competitors, effectiveness of mechanisms of appropriability (patents and other legal mechanisms of protection, process technology complexity etc.,) number of total competitors and competing innovators in each industry estimated by the R&D unit managers, among other variables.

2. The model

There are two groups of firms that compete *a la Cournot* in a homogenous product market. The production stage is preceded by a process-innovation investment stage, where a group of firms undertakes cost reducing R&D and benefits from the spillover of new knowledge generated by competitors' R&D projects. The other group of firms does not invest in R&D but still reduces costs through absorption of knowledge generated by the R&D undertaking firms. Asymmetry in the industry is thus introduced in the model by allowing firms to differ with respect to both their ability to generate process innovations (one type of firms undertake cost reducing R&D, the other type do not) and their ability to absorb knowledge spillovers from their rivals.

Costs per unit of output produced are linear and depend on the amount of R&D undertaken by the innovators[1]

$$c_{1i} = c - \theta_1 \Sigma R_j \quad (1)$$

$$c_{2j} = c - R_j - \theta_2 \Sigma R_{j-} \quad (2)$$

$$(i = 1,\ldots,N_1;\ j = 1,\ldots,N_2)$$

with $0 \leq \theta_1 < \theta_2 \leq 1$, $c > 0$, $\theta_1 \Sigma R_j < c$, $R_j + \theta_2 \Sigma R_j < c$.

The N_1 firms of type 1 (fringe firms, $N_1 \geq 0$) do not invest in research and development, but can benefit from the rivals' R&D (ΣR_j) by a fraction θ_1. The N_2 firms of type 2 (innovators, with $N_2 \geq 2$) actively invest in R&D (R_j) and benefit from the leakage of new knowledge generated by other innovators' R&D investments (ΣR_{j-}) by a fraction θ_2. The spillover parameters, θ_1 and θ_2, are exogenous and reflect both firms' ability to absorb knowledge generated by innovators and institutional-technological conditions (such as the effectiveness of patent protection and the nature of knowledge to be protected.) We assume that $\theta_1 < \theta_2$, so that the fringe firms are less capable than the innovators with

---

[1] c_{1i} represents the cost per unit of output of the ith firm of type 1 (for $i=1,\ldots,N_1$), the non-performers of R&D, whereas c_{2j} represents the cost per unit of output of the jth firm of type 2 (for $j=1,\ldots,N_2$), the R&D

respect to both their ability to generate innovations (they do not conduct R&D) and their ability and/or possibility to benefit from within-industry knowledge spillovers[2].

Firms face a linear inverse demand

$$p = a - b \cdot Q \qquad (3)$$

with $Q = \Sigma q_{1i} + \Sigma q_{2j}$ ($i = 1,\ldots,N_1$; $j = 1,\ldots,N_2$), $a,b > 0$, and $a>bQ$. Note that the constant c in unit costs (1) and (2) must be less than a, the intercept of the inverse demand (3), so that

$a-c>0$.

2.1 Equilibria

In the first stage of the game, R&D performing firms choose the optimal amount of R&D, given the product quantities that will result from the subsequent production stage. In the second stage all the firms choose the optimal level of production given the R&D level that result from the first stage. We look for a subgame perfect equilibrium using backward induction.

2.1.1 The second period (production stage)

Profits from production for the two type of firms are

$$\pi_{1i} = (p - c_{1i})\, q_{1i} \qquad (4)$$

$$\pi_{2j} = (p - c_{2j})\, q_{2j} \qquad (5)$$

$$(i = 1,\ldots,N_1;\ j = 1,\ldots,N_2)$$

Each firm maximizes profits by choosing the optimal amount to produce, given their competitors' quantities and the post-R&D costs determined in the preceding stage. The first order conditions give a system of $N=N_1+N_2$ simultaneous equations (reaction functions), whose solution represent the Cournot-Nash equilibrium quantities in the product market:

---

performers. We omit the double subscript for the R&D choice variable, R_j, because only the type-2 firms invest in R&D.

[2] Empirical studies suggest that R&D performers are more likely to be successful in absorbing knowledge generated outside their R&D labs (see Mowery, 1983, among others.)

$$q_{1i}^{c} = \frac{1}{b \cdot G} \cdot \left(a - c - A \cdot \sum_{j=1}^{N_2} R_j \right) \tag{6}$$

$$q_{2j}^{c} = \frac{1}{b \cdot G} \cdot \left(a - c + B \cdot R_j + D \cdot \sum_{k \neq j} R_k \right) \tag{7}$$

with

$$\begin{aligned} A &\equiv N_2\theta_2 - N_2\theta_1 + 1 - \theta_1 - \theta_2 \\ B &\equiv N_1 + N_2 - N_1\theta_1 - N_2\theta_2 + \theta_2 > 0 \\ D &\equiv N_1\theta_2 - N_1\theta_1 + 2\theta_2 - 1 \\ G &\equiv N_1 + N_2 + 1 > 0 \end{aligned} \tag{8}$$

Note that the linearity of demand and unit costs assure the stability of the equilibrium of the production stage (Hahn, 1962).

We then calculate the equilibrium level of price, p, given firms' and industry's costs. The equilibrium profits from production for the two types of firms become

$$\pi_{1i}^{q} = b \cdot \left(q_{1i}^{c} \right)^2 ; \tag{9}$$

$$\pi_{2j}^{q} = b \cdot \left(q_{2j}^{c} \right)^2 . \tag{10}$$

$(i = 1,\ldots..,N_1;\ j = 1,\ldots..,N_2)$

2.1.2 The first period (R&D stage)

Only firms of type 2 will undertake cost reducing R&D. The investments are made with diminishing returns. The N_2 objective functions for these firms are

$$\underset{R_j}{Max}\, \pi_{2j} = b \cdot \left(q_{2j}^{c} \right)^2 - \frac{f}{2} R_j^2 = \frac{1}{bG^2} \cdot \left(a - c + BR_j + D \cdot \sum_{k \neq j} R_k \right)^2 - \frac{f}{2} R_j^2 \tag{11}$$

$(j = 1,\ldots..,N_2)$

with B, G and D defined in (8.) The exogenous parameter f reflects the efficiency of the existing R&D technology, with f > 0.

The N_2 firms of type 2 maximize profits by choosing the optimal level of cost reducing R&D, given the R&D levels of their rivals. The first order conditions give a system of N_2 equations (reaction functions), whose solution represents a Nash equilibrium in R&D levels.

We will assume symmetry at this stage by setting $R_1 = R_2 = \ldots = R_{N_2} = R$ in each of the N_2 first order conditions and get the Nash equilibrium level of R&D that will be the same, in equilibrium, for all the N_2 innovators:

$$R = \frac{(a-c)\cdot B}{\frac{f\cdot b}{2}\cdot G^2 - B\cdot\left[B + (N_2 - 1)\cdot D\right]} \tag{12}$$

with B, G, and D defined in (8.) Note that a-c, B, and G are always >0 (with G>B.) The second order condition requires

$$B^2 - \frac{fb}{2}G^2 < 0 \tag{13}$$

We also derive stability conditions for the N_2-firm symmetric equilibrium in the R&D game. We can write the stability conditions as[3]:

$$S_1 \equiv \frac{fb}{2}G^2 - B\left[B - (N_2 - 1)D\right] > 0, \qquad \text{for } D < 0 \tag{14}$$

$$S_2 \equiv \frac{fb}{2}G^2 - B\left[B + (N_2 - 1)D\right] > 0, \qquad \text{for } D > 0 \tag{15}$$

with B, D, and G defined in (8.) Stability conditions (14,15) assure positive R&D for the type-2 firms, and positive quantities and profits for both type of firms in equilibrium[4]. Note that S_2 is equal to the denominator of (12), the R&D equilibrium level, so that it is easy to verify that (15) implies positive R&D investments.

---

[3] Stability implies (see Dixit, 1986) that $\frac{\partial^2\pi_{2j}}{\partial R_j \partial R_j} \pm (N_2 - 1)\cdot\frac{\partial^2\pi_{2j}}{\partial R_j \partial R_k} < 0$, for k≠j, that is $\frac{2B^2 - fbG^2}{bG^2} \pm (N_2 - 1)\frac{2BD}{bG^2} < 0$. We need two stability conditions because the sign of $\frac{\partial^2\pi_{2j}}{\partial R_j \partial R_k} = \frac{2BD}{bG^2}$ is ambiguous (b,B, and G are >0, but the sign of D is ambiguous.) Indeed, R&D investments are strategic substitutes (complements) when $D = N_1(\theta_2 - \theta_1) + 2\theta_2 - 1$ is less (greater) than zero. D will be positive when $N_1 > (1-2\theta_2)/(\theta_2 - \theta_1)$. Note that with $\theta_2 > \theta_1$, a sufficient condition for D>0 is $\theta_2 > 1/2$. But D can also be positive when $\theta_2 < 1/2$, if $\theta_2 - \theta_1$ is not too small and N_1 is large. Note also that in order to achieve stability in this model we basically need a low $(\theta_2 - \theta_1)$ or a low N_1 or a low N_2 compared to f and b. It can be shown that stability is always achieved either by setting $fb > 2N_2$ or $fb > 2[N_1(\theta_2 - \theta_1) + \theta_2]$.

[4] By manipulating S_1 and S_2, and solving the inequalities for fb (the R&D efficiency parameter multiplied by the slope of the inverse demand function), it can be easily verified that the value of fb required for stability when D>0 is always greater than the value of fb required for stability when D<0.

Finally, quantities and costs in equilibrium can be obtained by expanding the following:

$$q_1 = \frac{1}{b \cdot G} \cdot \left(a - c - A \cdot N_2 R\right) \tag{16}$$

$$q_2 = \frac{1}{b \cdot G} \cdot \left\{a - c + \left[B + \left(N_2 - 1\right) \cdot D\right] \cdot R\right\} \tag{17}$$

$$c_1 = c - \theta_1 N_2 R \tag{18}$$

$$c_2 = c - \left[1 + \theta_2 \left(N_2 - 1\right)\right] \cdot R \tag{19}$$

with A,B,D and G defined in (8), and R being the equilibrium level of R&D represented by equation (12.) Note that $c_2<c_1$, that is, costs per unit of output in equilibrium for the R&D performers will always be lower than those of the fringe firms[5]. It can also be verified that cost differences imply that innovators will always produce more in equilibrium, that is $q_2>q_1$.

2.2 Comparative statics

We have built a theoretical model that allow us to analyze the effect of changes in the parameters of interest on R&D investments, firms' profits and welfare. The parameters of interest are: N_1, the number of fringe firms, who can lower their costs only through process innovations-related knowledge spillovers generated by the R&D performing rivals; θ_1, the spillover parameter representing the extent to which the total R&D performed in the industry will lower the costs of the N_1 non-performers; N_2, the number of R&D performers; θ_2, the spillover parameter representing the extent to which the production cost of an R&D undertaking firm will be lowered by the total R&D of her rivals.

In the following paragraphs we present the most interesting comparative static results, leaving proofs in the Appendix.

2.2.1 Spillovers and R&D investments

PROPOSITION 1: $\frac{\partial R}{\partial \theta_1} < 0$ *.*

---

[5] Indeed, $c_1 - c_2 = \left[N_2\left(\theta_2 - \theta_1\right) + 1 - \theta_2\right] \cdot R > 0$: the R&D performers are always more efficient than the fringe firms in the model (unless $\theta_2=\theta_1=1$, a case that we exclude by assumption.)

Larger spillovers benefiting the fringe firms (θ_1) will always discourage R&D investments. The intuition behind this result is that unilateral flows of knowledge from innovators to fringe firms have only one effect: they will reduce costs of the fringe firms, increase their quantities and market shares at the expenses of innovators, that are involuntary “loosing” part of the generated new knowledge, with an unambiguously negative disincentive effect on the level of R&D.

The above result is not particularly surprising, but the previous literature has overlooked this basic effect because when the population analyzed is that of identical R&D performers only, spillovers are reciprocal in nature: innovators “loose and steal” new knowledge from their R&D rivals, their unit costs may decrease as a result but market shares would never change. The key fact, though, is that the very existence of non innovators (high cost firms) in the industry will also condition the effect of reciprocal spillovers among identical innovators on their R&D, as shown in the following proposition2.

The analysis of the effect of larger spillovers among innovators (θ_2) on their R&D investments reveals that the sign of the comparative static is ambiguous. In particular, $\frac{\partial R}{\partial \theta_2} > 0$ *if and only if*

$$\Phi \equiv \frac{fb}{2} \cdot (N_1 + N_2 + 1)^2 - (N_1 + 1) \cdot [N_1(1 - \theta_1) + N_2(1 - \theta_2) + \theta_2]^2 < 0 \qquad (20)$$

Analysis of (20) allows us to state the following result[6]:

PROPOSITION 2:

i) $N_1 = 0 \Rightarrow \frac{\partial R}{\partial \theta_2} < 0.$

ii) $\exists\, N_1^* > 0 \;\middle|\; N_1 > N_1^* \Rightarrow \frac{\partial R}{\partial \theta_2} > 0.$

Proposition 2 says that: i) Larger spillovers among innovators (θ_2) will always decrease the equilibrium level of their R&D investments when the number of fringe firms is zero; ii) If the number of fringe firms is sufficiently large (with the critical value of N_1

---

[6] The critical value N_1^* in the following proposition is a function of the other parameters of the model.

being positive and a function of all the other parameters), larger spillovers benefiting the innovators will always increase the equilibrium level of R&D investments[7].

The intuition behind the result is the following. Larger spillovers among the innovators have a negative disincentive effect and a positive market expansion effect. The disincentive effect is due to the fact that R&D performed by one innovator will reduce costs of other innovators, via spillovers. The positive market expansion effect is due to the fact that spillovers among innovators reduce their costs and increase their market shares, but in a world of identical R&D performers, without fringe firms, this market share effect is zero. When $N_1>0$, the cost reduction of the innovators due to spillovers will instead translate in larger market shares for the innovators at the expenses of the fringe firms, thus providing a positive effect on R&D levels. The net effect on equilibrium R&D will then depend upon the sum of the two offsetting effects. Proposition 2, however, tells us that for a sufficiently large number of fringe firms, the positive market expansion effect will prevail, and larger spillovers among innovators will stimulate R&D equilibrium levels[8]. Note also that the critical value of N_1, above which the marginal effect of spillovers become positive, will be lower the lower is the amount of knowledge that the fringe firms are able to "steal" from the innovators.

To our knowledge, involuntary and reciprocal spillovers among non cooperating R&D performing firms in a symmetric oligopoly with strategic cost reducing investments and homogenous good competition, have been shown to always have a negative effect on the level of R&D investments (see De Bondt, 1996 for a review of this literature.) The only exceptions are the models of Cohen and Levinthal (1989) and Levin and Reiss (1988). The former authors show that if spillovers are endogenous, in the sense that greater R&D increases firms' ability to absorb spillovers, then it is also possible that greater spillovers provide a net positive incentive effect on R&D levels. Levin and Reiss show that if knowledge generated by R&D investments of one firm is complementary to

---

[7] Proposition 2 does not imply that the relationship between N_1 and the marginal effect of spillovers among innovators on R&D is monotonic. It could indeed be shown that as N_1 grows very large the marginal effect of spillovers, although it remains positive, tends to decline. Analytically, this means that the sign of the mixed partial effect $\partial^2 R/\partial\theta_2\partial N_1$ is ambiguous; empirically, this means that proposition 2 is difficult to test.

[8] Note also from (20) that when R&D is very costly (f is high) and elasticity of demand is low (b is high) greater spillovers among innovators tend to temper R&D effort. In such a case, the critical level of N_1 - above which $dR/d\theta_2$ is always positive - will be larger.

that generated by an R&D rival, then knowledge spillovers among R&D rivals might increase the productivity of own R&D, thus providing a positive incentive effect on R&D levels. None of the explanations above relies on the role of competition to explain why spillovers may encourage R&D, and we also conjecture that those alternative explanations would complement the market expansion effect of spillovers that is driving the results presented in our model.

It is useful to look at some numerical simulations of the equilibrium value of R&D as a function of the two spillover parameters (θ_1 and θ_2) in two industries that only differ with respect to the number of fringe firms[9].

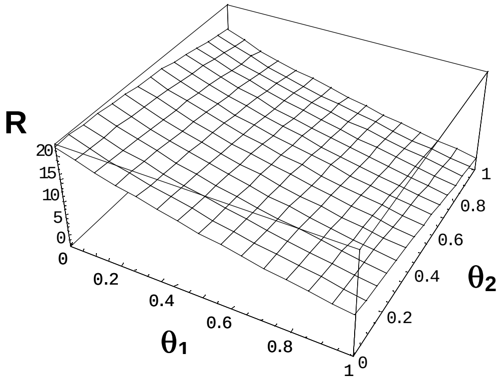

Figure 1 Effect of spillovers among fringe firms (θ_1) and innovators (θ_2) on R&D with <u>low</u> N_1

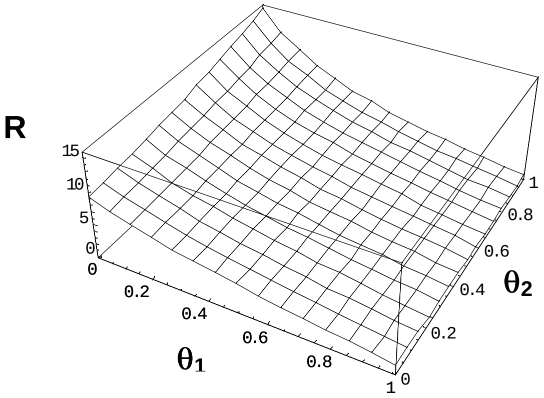

Figure 2. Effect of spillovers among fringe firms (θ_1) and innovators (θ_2) on R&D with <u>large</u> N_1

Note that in Fig. 1, representing an industry with a small number of fringe firms, both larger spillovers benefiting the fringe firms (θ_1) and larger spillovers among innovators (θ_2) have a negative effect on R&D. In Fig. 2, where the number of fringe firms is larger,

---

[9] To obtain the simulations we used the following parameter values: a-c=1000; b=2; f=5 – these values are the same in Fig.1 and 2; N_1=4 and N_2=4 (Fig. 1); N_1=20 and N_2=4 (Fig. 2). The software used for the

larger spillovers benefiting the fringe firms still have a negative effect on R&D, but larger spillovers among innovators now have a positive effect on R&D.

2.2.2 R&D and the number of capable and incapable rivals.

Analysis of the effect of entry of either a fringe firm or an innovator on R&D incentives does not yield unambiguous results. Intuition, however, suggests that the effect of entry of an innovator should differ systematically from that of entry of a fringe firm because in this model, fringe firms' units costs are always larger than innovators' unit costs (see footnote 5.) The comparative static analysis presented in this section confirms this intuition and yields interesting and novel results.

Entry of a fringe firm has an ambiguous effect on equilibrium R&D investments[10]. The following proposition establishes a sufficient condition under which the effect of entry of a fringe firm is positive[11].

PROPOSITION 3:

$$\exists \quad \theta_1^*, \theta_2^*, N_2^* \quad \Big| \quad \theta_1 < \theta_1^* \textit{ and } \quad \theta_2 > \theta_2^* \textit{ and } N_2 > N_2^* \Rightarrow \frac{\partial R}{\partial N_1} > 0 \quad .$$

. Proposition 3 says that if the industry is populated by fringe firms with low capabilities at absorbing knowledge generated by innovators (θ_1 low), and by a large number of innovators (N_2 large) with large spillovers among them (θ_2 large), then a larger number of fringe firms will always stimulate R&D efforts.

The intuition behind this result is that when a fringe firm enters in the industry, there are two opposite effects on R&D levels. Quantities produced by all the firms in the industry will decrease, thus providing a negative disincentive effect on R&D. On the other hand, an additional fringe firm translates in a positive new market share that the innovators could potentially "steal" with larger R&D efforts. If R&D is sufficiently efficient,

---

simulations is Mathematica. The use of the software was also critical for the derivation of the analytical results presented in this paper.

[10] The sign of $\frac{\partial R}{\partial N_1} = \frac{(a-c)\left\{B^2\left[N_2(\theta_2-\theta_1)+1-\theta_2\right]-\frac{fb}{2}G\left[2B-(1-\theta_1)G\right]\right\}}{[illegible]^2}$ is ambiguous, with B,G defined in (8), f,b>0, a-c>0. The expression that multiplies B^2 in the numerator, indeed, is always positive, whereas the expression that multiplies -(fb/2)G has ambiguous sign. Similarly, the relationship between B^2 and (fb/2)G is ambiguous.

[11] The critical values (denoted with a "*") of the following proposition are each a different function of the other parameters of the model.

and if the fringe firms do not significantly free-ride on R&D performers' generated knowledge, the "stealing market share" incentive effect will prevail on the disincentive effect of entry of a fringe firm[12].

Analysis of the effect of entry of an innovator on R&D incentives reveals that also this comparative static has an ambiguous sign[13]. The following proposition establishes sufficient conditions under which the effect of entry of an innovator is negative or positive[14].

PROPOSITION 4:

i) $\exists \ b^*, f^* \ \Big| \ b > b^* \ \textit{or} \ f > f^* \Rightarrow \dfrac{\partial R}{\partial N_2} < 0$

ii) $N_1 = 0 \Rightarrow \dfrac{\partial R}{\partial N_2} < 0$

iii) If $N_1 > 0, \ \exists \ b^{**}, f^{**}, \theta_2^{**}, N_2^{**} \ \Big| \ \left(b < b^{**} \ \textit{or} \ f < f^{**}\right) \textit{and} \ \theta_2 < \theta_2^{**} \ \textit{and} \ N_2 < N_2^{**} \Rightarrow \dfrac{\partial R}{\partial N_2} > 0$

Proposition 4-i says that when the elasticity of demand is sufficiently low (b is high) and/or the cost of R&D is sufficiently high (f is high), entry of an innovator has a negative effect on the equilibrium level of R&D. The reason behind this result is that a larger f (R&D cost parameter) unambiguously increase the marginal cost of R&D, whereas a larger b (lower elasticity of demand) unambiguously decrease the marginal benefit of investing in R&D (it is easy to understand this by looking at the innovators' objective function (11).). If these parameters are sufficiently high, any ambiguity of the effect of a larger number or innovators will disappear.

---

[12] Proposition 3 is counterintuitive, to some extent. Let us summarize the relationship between the critical values of the parameters presented in proposition 3 and the intuition presented in the text in more detail. In order to obtain the result that entry of a fringe firm stimulates R&D efforts we need: 1) a low θ_1, because the unambiguous disincentive effect of this parameter on R&D (see prop.1) will be low; 2) a large θ_2, because large reciprocal spillovers among innovators makes R&D more efficient (less duplicative research, "efficiency effect"...); 3) a large N_2, because even though this would translate in lower quantities and thus in a lower incentive to do R&D, a large N_2 also means a higher efficiency of R&D.

[13] The sign of $\dfrac{\partial R}{\partial N_2} = \dfrac{(a-c)\left\{B^2\left[N_1(\theta_2-\theta_1)+\theta_2\right]-\dfrac{fb}{2}G\left[2B-(1-\theta_2)G\right]\right\}}{S_2^{\,2}}$ is ambiguous, because the expression that multiplies B^2 in the numerator is always positive, as it is the expression that multiplies –(fb/2)G.

[14] The critical values (denoted with a "*" or "**") of the following proposition are each a different function of the other parameters of the model.

Proposition 4-ii basically says that the ambiguity of the effect of entry of an innovator on R&D efforts is due to the very existence of non innovators in the industry. If we set $N_1=0$, like in the standard models of identical R&D performers, $\partial R/\partial N_2$ is always negative, and this result is consistent with the comparative static results of similar homogenous oligopoly models with identical firms (see for example De Bondt et al., 1992.) Again, we need at least some fringe firms to change the effect of entry of innovators on R&D from negative to positive because of the incentive that these inefficient firms provides for additional R&D efforts.

Proposition 4-iii is counterintuitive and novel with respect to the existing literature: it says that if the elasticity of demand is sufficiently high (b is low) or the cost of R&D is sufficiently low (f is low) and also the spillovers among innovators are sufficiently low and the number of innovators is sufficiently low, then entry of an innovator stimulates R&D efforts, provided that the number of fringe firms is greater than zero.

It is clear that only under exceptional circumstances a larger number of innovators has a positive effect on R&D. Intuitively, the result is due to the fact that entry of an innovator in the industry has in principle two conflicting effects on R&D effort: on one hand, quantities produced by all the firms in the industry will decrease, thus providing a negative disincentive effect on R&D; on the other hand, an additional innovator makes R&D in the industry more efficient (it increases the amount of knowledge available in the industry), thus providing an incentive effect on R&D effort if there are fringe firms in the industry. The proposition implies that the incentive effect will dominate the negative effect if N_2 is sufficiently low and θ_2 is sufficiently low and if the R&D cost is sufficiently low and/or elasticity of demand is sufficiently large.

The above propositions 3 and 4 present interesting and counterintuitive results that highlight the importance of including the technologically incapable firms in the analysis of R&D incentives. The results, however, depend on critical values of the parameters that depend, in turn, on a combination of other parameters of the model that we cannot observe, such as for example the R&D cost parameter, or the elasticity of demand.

The above analysis, however, suggests that the difference between the effect of entry of a fringe firm and the effect of entry of an innovator is significant. In particular, proposition 3 and proposition 4-iii suggest an interesting pattern: when the number of innovators in the industry is large and the spillovers among them are also large the effect of entry of a fringe firm tends to be positive, whereas the effect of entry of an innovator tends to be negative (or at least to decrease).

Indeed, a deeper investigation of the relationship between the two effects allow us to state the following result:

PROPOSITION 5:

$$\textit{If } \theta_1 \cong 0 \textit{ or } \theta_2 - \theta_1 > \delta^*, \textit{with } 0 < \delta^* \leq 1, \textit{ then}$$

$$\frac{\partial R}{\partial N_2} < 0 \Rightarrow \frac{\partial R}{\partial N_1} - \frac{\partial R}{\partial N_2} > 0$$

Proposition 5 says that if the firms who do not perform R&D are not able to absorb a fraction of knowledge from the innovators that is significantly different than zero (θ_1 is approximately zero) or the differences among fringe firms and innovators in absorbing within-industry spillovers are sufficiently large (θ_2-θ_1 is sufficiently large), than a negative effect of entry of an innovator implies that entry of an N_2 type lowers R&D by a larger amount than entry of an N_1 type.

In general, this is very close to what intuition would suggest: if there are significant technological differences among the two groups of firms, we would at least expect that entry of an innovator has a more negative effect than the entry of a fringe firms, because lower costs, in this model, mean larger market shares[15].

Proposition 5, then, is an economic plausible result that, as we will see shortly, can be tested empirically.

2.2.3 The appropriability problem and the conditioning role of competition.

---

[15] Cost differences, and thus market share differences, are not only due to the different capabilities of the two type of firms at generating technological innovations (a group of firms undertakes R&D, the other does not). The difference between unit costs among the two type of firms in equilibrium, $c_1 - c_2 = [N_2(\theta_2 - \theta_1) + 1 - \theta_2] \cdot R > 0$, depends critically on the difference θ_2-θ_1, that is on the difference between abilities to exploit within industry knowledge spillovers. If then we assume that θ_1 is approximately equal to zero or that θ_2-θ_1 is sufficiently large, we are basically assuming that there significant cost differences between the two type of firms, or significant technological differences. Note that θ_1 close to zero also means a relatively larger R&D in equilibrium (see proposition 1) and thus larger cost differences among fringe firms and innovators.

One of the key issues of this paper is to understand the relationship between R&D, spillovers, and competition among rivals with asymmetric technological capabilities. We have seen that a negative effect of spillovers on R&D (the “appropriability problem”) is always present when knowledge generated by R&D performers unilaterally flows to non-performers. Reciprocal spillovers confined among R&D performers might instead increase R&D investments. On the other hand, the effect of greater competition in the industry depends critically on the technological capabilities of entrants.

This feature of the model leads us to analyze the following question: are industries with a greater number of R&D performers relative to the number of non performers characterized by a deeper appropriability problem (disincentive effect of spillovers greater)? Analytically, this amounts to sign the mixed partial derivative $\frac{\partial^2 R}{\partial \theta_2 \partial N_2}\Big|_{\overline{N}}$, that is the effect of a change in the mix of firms on the marginal effect of spillovers among innovators on R&D efforts[16].

A result of the comparative static analysis is the following proposition 6:

PROPOSITION 6

$$\frac{\partial R}{\partial \theta_2} < 0 \textit{ and } N_1 > \sqrt{\overline{N} - 1} \Rightarrow \frac{\partial^2 R}{\partial \theta_2 \partial N_2}\Big|_{\overline{N}} < 0.$$

Proposition 6 says that if the net effect of spillovers among innovators on R&D efforts is negative (an appropriability problem exists), than a larger number of innovators relative to the fringe firms would always increase such a disincentive effect, provided that the number of fringe firms relative to the innovators is sufficiently large. As we will see shortly, this result can be tested empirically because it depends on parameters that we observe.

We conclude the theoretical section of the paper with a note on social welfare. The analytical derivation of the effect of spillovers and entry on social welfare (defined as producer surplus plus consumer surplus), is quite involved and we will not pursue that here. Numerical simulations, however, show that spillovers confined among the

---

[16] Note that $\overline{N} = N_1 + N_2$ is a fixed number (we hold the size of the industry constant in this case.)

innovators stimulate social welfare under a wide range of values of the model parameters. Greater spillovers among innovators, indeed, always have an "efficiency effect" (Spence, 1984): for a given level of R&D investment, unit costs always decrease. Put in another way, the average productivity of R&D (reduction in unit costs per dollar spent in R&D) can be shown to always increase with spillovers. This positive effect is known in the literature. However, the introduction of technologically incapable rivals introduces an additional effect on social welfare. If spillovers make R&D more efficient and reduce costs, they will also stimulate the quantity produced by the innovators. To the extent that the fringe firms do not significantly free ride upon innovators' R&D, there will be a redistribution of market shares within the industry which favors the innovators, i.e. the low cost producers, with a positive effect on social welfare.

4. Empirical Analysis.

Is the theory developed in this paper amenable to empirical testing? Despite the simplifying assumptions of the model[17], we will use the predictions of the theory as a guide to interpret the empirical evidence, given the availability of unique survey data on R&D activities, spillovers among innovators, and competition in the United States. It is important however to underscore the fact that the empirical results presented in this section are only a partial test of the model for several reasons. In addition to the highly stylized structure of the model, only two predictions (proposition 5 and 6), which are not necessarily the most interesting ones, are testable, in the sense that they depends on parameter that we observe. Some results of the model, such as for example the first order effects of entry and larger spillovers on process R&D investments, depend on parameters that we do not observe (the efficiency of the R&D technology or the elasticity of demand.) Additionally, the data that we have, although unique, only provide indirect measures of the true underlying variables (such as for example our measure of the extent of knowledge spillovers among innovators.)

---

[17] There exists only two type of firms that differ in their exogenously given technological capabilities; they compete by non-cooperatively choosing quantities in a homogenous good market; we specified linear demand and cost functions; the number of firms is exogenous, among other assumptions.

4.1 Data and variables.

In the empirical section of the paper we use the 1994 Carnegie Mellon survey of industrial R&D in the United States[18]. The survey contains data on a sample of 1,478 R&D labs or units located in the U.S. conducting R&D in manufacturing industries. R&D unit managers were asked to answer questions related to their R&D activity with reference to the "focus industry" of their unit, defined as the principal industry for which the unit was conducting its R&D. The survey contains data on process related R&D, spillovers among innovators, number of capable and incapable innovators, and other industry level determinants of R&D investments, among other variables (Cohen, Nelson, and Walsh, 1997, contains a complete description of the survey's methods and results.)

The unit of observation in the survey is the R&D lab, but the basic structure of the model and the cross-section nature of the data lead us to empirically analyze the determinants of inter industry differences in the level of process R&D investments. On the other hand, the exogenous determinants of R&D considered in our theory are industry specific (the spillover parameter of the innovators, the number of capable and incapable rivals, demand and cost factors.) As a consequence, we will measure the variables at the industry level, by computing the 4 digit SIC average of R&D units responses[19]. Note also that the model considers homogeneous good competition and the use of data at a fairly detailed level of disaggregation allows us to control for the degree of product differentiation in each industry[20].

The following table presents the variables used in the empirical analysis and descriptive statistics. As we will see shortly, we include in the empirical specification additional variables to control for the technological opportunities in each industry, such as for example the importance of basic science to R&D activities, the growth of industry demand, and the age of the industry.

---

[18] The survey was administered in 1994 by sending questionnaires by mail and conducting follow-ups by telephone, see Cohen, Nelson, and Walsh, 1997.

[19] Some industries have been aggregated at the 3 digit SIC level in order to have at least 5 observations per industry.

[20] De Bondt, Slaets, and Cassiman, 1992, show that the degree of product differentiation within the industry will condition the relationship between spillovers, number of rivals and cost reducing R&D.

Table 1: Variables and descriptive statistics.

Variable	*Description*	*N*	*Mean*	*Std Dev*	*Min*	*Max*
R	Company financed R&D unit's expenditures (in mil. $) devoted to new or improved processes	73	1.92	2.31	0.06	15.98
θ_2	Composite measure of spillovers among innovators	73	12.21	4.07	6.33	23.11
N_1	Number of fringe firms	73	20.05	11.14	3.55	57.25
N_2	Number of innovators	73	9.70	6.11	2.58	37.82
SCIENCE	Importance of Science to R&D unit's activities	73	3.25	0.28	2.53	3.81
UNIVSPIL	Frequency of interaction with universities/government research (n. of "contact days" per year)	73	16.88	17.56	0.88	71.71
DEMGRW	% change in industry sales between 1987-'92	73	4.51	2.82	-4.05	11.57
MATURE	Number of years since the year of entry in the industry of each firm	73	47.43	18.30	14.50	96.43

Appendix 2 contains a more detailed explanation of the variables used. Here, it is important to highlight two important points. Our measure of θ_2, the spillover among innovators variable, is a composite indicator constructed by calculating industry means of several spillover related variables and dividing each mean by the within industry standard deviation. In particular, we used the following variables: 1) the frequency with which R&D units obtain useful technical information from competitors worldwide; 2) the percentage of R&D units in each industry obtaining information from rivals' R&D suggesting new R&D projects or contributing to completion of existing R&D projects; 3) the effectiveness of patents and other legal mechanisms in protecting the returns process innovations; 4) the complexity of processes' technology[21]. Our measure of θ_2 is then the sum of different standardized measures. The simple sum can be justified by

---

[21] The effectiveness of the legal system in protecting firms' returns from their innovations and the nature of the technology itself are treated as exogenous conditions that influence the level of knowledge spillovers in the industry.

considering that the variables used in constructing the composite indicator represent different dimensions of the spillovers mechanism.

Another point to highlight is related to our measure of the number of fringe firms and innovators in each industry. In our model the fringe firms are those firms who do not perform R&D and possess relatively lower capabilities to absorb knowledge spillovers from the innovators. We do not have a direct measure of this variable. The survey questionnaire, however, asks R&D managers to estimate both the total number of competitors and the number of competing innovators their firm has worldwide in their focus industry. We then calculated the number of fringe firms in each industry as the difference between the total number of competitors and the number of competing innovators.

4.2 Empirical specification and results.

To summarize, the theory offers two testable predictions, corresponding to propositions 5 and 6. Proposition 5 predicts that when a larger number of innovators has a negative effect on process R&D ($\partial R \backslash \partial N_2 < 0$) and the fringe firms absorb a low level of R&D spillovers or sufficiently lower than the innovators (θ_1 is low or $\theta_2 - \theta_1$ is high), then the entry of a fringe firm has a lower disincentive effect on process R&D than the entry of an innovator ($\partial R \backslash \partial N_1 - \partial R \backslash \partial N_2 > 0$). We do not have measures for the spillover parameter of the fringe firms, θ_1, but the assumption that this parameter is approximately zero is plausible. The fringe firms do not have capabilities to actively generate technological innovations, and even though they may absorb some positive level of R&D spillovers, the fraction absorbed is likely to be very small (see also footnote 15.) We then expect the empirical results to be consistent with proposition 5.

Proposition 6, on the other hand, says that if larger spillovers among innovators have a disincentive effect on process R&D ($\partial R \backslash \partial \theta_2 < 0$), then an increase in the number of innovators relative to the fringe firms will render the disincentive effect of spillovers larger ($\partial^2 R \backslash \partial \theta_2 \partial N_2 < 0$, holding the total number of firms constant). This prediction holds when the number of fringe firms relative to the number of innovators is larger than a critical threshold. In our sample, all the industries met the selection criteria (i.e., have a sufficiently large number of fringe firms given the total number of firms in the industry, as indicated in proposition 6.)

In order to analyze whether the data are consistent with these two propositions we then employed the following specification[22]:

$$\begin{aligned} R = {} & \beta_1 + \beta_2\theta_2 + \beta_3 N_1 + \beta_4 N_2 + \beta_5 (N_1 \cdot \theta_2) + \beta_6 (N_2 \cdot \theta_2) + \\ & \beta_7 \text{SCIENCE} + \beta_8 \text{UNIVSPIL} + \beta_9 \text{DEMGRW} + \beta_{10} \text{MATURE} \end{aligned} \tag{21}$$

In addition to the variable described in Table 1, we included two interaction terms, constructed by multiplying respectively the number of fringe firms and the number of innovators with the spillover variable. The inclusion of the two interaction terms is needed in order to recover the sign and the magnitude of the conditioning role of entry on the relationship between spillovers and R&D. We also include other industry determinants of R&D investments as controls. These are: the importance to R&D units' activities of basic science (SCIENCE) and the frequency of knowledge related interactions between R&D units and universities or government research labs (UNIVSPIL), considered to be two sources of industrial technological opportunity (technical advance per unit of R&D effort;) the age of the industry, included in the empirical specification as a control for the maturity of the industry[23]; a time shift parameter (DMGRW) reflecting the % change of industry sales between 1987-'92.

The following tables present the results of the regression analysis obtained using specification (21). Table 2.1 presents the OLS regression results. Table 2.2, part a), b), and c) presents estimates of the first order effects of the independent variables that are interacted (θ_2, N_1 and N_2) using the sample means of the these variables; Table 2.2, parts d) and e) shows the results of the hypothesis tests related to proposition 5 and 6.

Note that using a Breusch-Pagan statistic to test for heteroscedasticity, we rejected the null hypothesis of homoscedasticity. We then used heteroscedasticity-consistent standard errors to perform the hypothesis tests (White, 1980).

---

[22] We omit the variables' industry subscript.

[23] Klepper (1996) shows that as industries mature over time firms devote more effort to process innovation.

Table 2.1: Effects of spillovers and the number of rivals on process R&D

Dependent Variable: Industry average process R&D (R)

Parameter	*Variable*	*Estimate*	*Standard Error*$^{+}$	*T for H_0: Parameter=0*
β_1	CONSTANT	-1.3692	3.1394	-0.44
β_2	θ_2	-0.2307 *	0.1242	-1.86
β_3	N_1	-0.2384	0.1508	-1.58
β_4	N_2	0.2421	0.1940	1.25
β_5	$N_1\theta_2$	0.0267 *	0.0148	1.81
β_6	$N_2\theta_2$	-0.0338 *	0.0189	-1.79
β_7	SCIENCE	1.5745 **	0.7394	2.13
β_8	UNIVSPIL	0.0509 ***	0.0154	3.31
β_9	DEMGRW	-0.0734	0.0895	-0.82
β_{10}	MATURE	0.0060	0.0130	0.46

Number of Obs. = 73
R^2=0.41

** Significant at the 0.10 level. ** Significant at the 0.05 level. *** Significant at the 0.01 level.*

$^{+}$ *Heteroscedasticity-Consistent Standard Errors*

Table 2.2: Test of hypothesis

Effect	*Estimate*	*Standard Error*$^{+}$	*T for H_0: Effect=0*
a) $\delta R/\delta\theta_2$ $(\beta_2 + 20.3*\beta_5 + 9.7*\beta_6)$	-0.0192	0.0679	-0.28
b) $\delta R/\delta N_1$ $(\beta_3 + 12.2*\beta_5)$	0.0870 **	0.0398	2.19
c) $\delta R/\delta N_2$ $(\beta_4 + 12.2*\beta_6)$	-0.1711 **	0.0814	-2.10
d) $\delta R/\delta N_1 - \delta R/\delta N_2$ $(\beta_3 + 12.2*\beta_5 - \beta_4 - 12.2*\beta_6)$	0.2581 **	0.1179	2.19
e) $\delta^2 R/\delta\theta_2\delta N_2 - \delta^2 R/d\theta_2\delta N_1$ $(\beta_6 - \beta_5)$	-0.0605 *	0.0329	-1.84

** Significant at the 0.10 level. ** Significant at the 0.05 level.*

$^{+}$ *Heteroscedasticity-Consistent Standard Errors*

The coefficients of θ_2, N_1, and N_2 from the OLS regression presented in Table 2.1 do not represent the marginal effects of these variables on process R&D, because of the inclusion of interactions. The sign, magnitude, and significance of the coefficients of the interactions do however represent the conditioning role of entry of a fringe firm and an innovator on the level of process R&D investments (β_5 and β_6 respectively.) Even though the theory does not imply unambiguous signs for each of these coefficients, it is quite interesting how different the conditioning role of competition is depending on the type of firm we consider. The positive and significant (at the 10% level) estimate of β_5, for example, implies that in industries where the number of fringe firms is high, larger spillovers among innovators will increase the level of cost reducing R&D, a result that recalls proposition 2. The opposite result is obtained when we consider a larger number of innovators (β_6 is negative and significant at the 10% level.)

Do the results support propositions 5 and 6 of the theory? In order for the result of proposition 5 to hold we need to calculate the first order effect of a larger number of innovators (N_2) on process R&D investments using the sample mean of θ_2 (that is interacted with N_2) as shown in Table 2.2 part c. The sign of this effect is negative and we reject at the 5% significance level the null hypothesis that the effect is zero. Proposition 5 says that in the presence of such a negative effect, an increase in the fraction of fringe firms relative to the innovators will stimulate cost reducing R&D. Indeed, table 2.2 part d) shows that the empirical evidence is consistent with this result, implying that a marginal increase in the number of fringe firms and a marginal decrease in the number of innovators (i.e. an increase in the fraction of fringe firms relative to the innovators) would increase the industry average investments in process R&D by $258,000.

To empirically verify the result of proposition 6 we first need to calculate the first order effect of larger spillovers among innovators (θ_2) on process R&D investments, as shown in Table 2.2.a. The sign of this effect is negative, meaning that larger spillover have a disincentive effect on R&D investments, but we cannot reject the null hypothesis that the effect is zero. Proposition 6 says that in the presence of a disincentive effect of spillovers, an increase in the fraction of innovators relative to the fringe firms would render the disincentive effect of spillovers larger. The estimate presented in table 2.2.e is consistent with the theoretical result, because it implies that a marginal increase in the number of innovators and a marginal decrease in the number of fringe firms would decrease the disincentive effect of spillovers on process R&D by $60,495.

5. Conclusions.

The main objective of this paper is to show both theoretically and empirically that differences in firms' innovative capabilities at generating technical change and absorbing knowledge spillovers from rivals critically affects R&D investments. We built a simple model, intended to capture such asymmetries by introducing two types of firms in the industry, the fringe firms and the innovators, and used it as a guide to specify our empirical model and interpret the available evidence.

The comparative static results imply that process R&D investments critically depends on the extent of R&D-related knowledge spillovers across capable and incapable firms. The effect of spillovers on R&D, however, is not always negative (as implied by similar models of R&D competition.) Our model shows that spillovers benefiting the fringe firms always have a disincentive effect on R&D investments, whereas larger spillovers among innovators may stimulate cost reducing R&D investments. The available data allow us to measure only the extent of spillovers among innovators, and the empirical evidence appears to be consistent with the result that when the number of incapable firms is large, knowledge flows confined among innovators have a positive effect on R&D levels.

The theoretical analysis has also evidenced that entry of new competitors in the industry has a substantially different effect on R&D, depending on the entrants’ capabilities. An entrant with low capabilities at generating innovations and absorbing knowledge spillovers will get lower market shares and thus will provide a lower disincentive effect on R&D compared to a more capable innovator. In other words, the composition of the industry in term of fringe firms and innovators will critically affect R&D incentives both directly and via its conditioning effect on knowledge spillovers, a fact that has been neglected by both by the theoretical and empirical literature. The empirical results are consistent with the theoretical results.

Our analysis requires additional investigation. From a theoretical point of view, it appears to be promising a rigorous analysis of the effect of spillovers and competition on social welfare. We could also relax some simplifying assumptions, such as the exogeneity of the number of firms in the industry. From an empirical point of view, the robustness of the results could be improved by improving our measure of some of the variables. In particular, it would be appropriate to construct a composite indicator of the multiple spillover variables available in our survey data using factor analysis.

APPENDIX I: PROOF OF PROPOSITIONS.

Proof of PROPOSITION 1

The following partial derivative, $\frac{\partial R^*}{\partial \theta_1} = -\frac{N_1(a-c)\cdot\left(\frac{fb}{2}G^2 + N_2 B^2\right)}{S_2^{\,2}} < 0$ because B,G>0, defined in (8), a-c,f,b > 0 by assumption, and $N_1>0$ in order for the comparative static be meaningful.

Proof of PROPOSITION 2

i) Φ, defined in (20), evaluated at $N_1=0$ is equal to the left-hand-side of the S.O.C. (13) multiplied by (–1), which must be greater than zero. But Φ >0 is sufficient for $\frac{\partial R}{\partial \theta_2} < 0$ by (20).

ii) By expanding Φ, defined in (20), we get $\Phi = N_1\left[N_1\left(P_2 - P_1N_1\right) + P_3\right]$ with P_1, P_2,P_3,P_4 being functions of all the parameters of the model except N_1. So, as N_1 grows, P_1, P_2,P_3,P_4 do not change, with the only important thing being that $P_1=(1-\theta_1)^2>0$. We then find that $\lim_{N_1 \to \infty} \Phi = (\infty)(\infty)(-\infty) = -\infty$. But $\Phi<0$ is sufficient for $\frac{\partial R}{\partial \theta_2} > 0$ by (20). So, $N_1=0$ implies $\frac{\partial R}{\partial \theta_2} < 0$, but when N_1 grows large $\frac{\partial R}{\partial \theta_2}$ tends to become negative. With Φ being a continuous function of N_1, proposition 2 follows.

Proof of PROPOSITION 3

The sign of $\frac{\partial R}{\partial N_1} = \frac{(a-c)\left\{B^2\left[N_2(\theta_2 - \theta_1) + 1 - \theta_2\right] - \frac{fb}{2}G\left[2B - (1-\theta_1)G\right]\right\}}{S_2^{\,2}}$ is ambiguous, with B,G defined in (8), f,b>0, a-c>0. The expression that multiplies B^2 in the numerator, indeed, is always positive, whereas the expression that multiplies -(fb/2)G has ambiguous sign. Similarly, the relationship between B^2 and (fb/2)G is ambiguous. Indeed, a sufficient condition for dR/dN_1 to be positive is that $2B - (1-\theta_1)G < 0$, i.e., that

$N_1(1-\theta_1) + \theta_1(N_2+1) + N_2(1-2\theta_2) + 2\theta_2 - 1 < 0$: it is easy to verify by inspection that when θ_1 is sufficiently low and θ_2 and N_2 are sufficiently large this expression becomes negative, and thus dR/dN_1 becomes positive.

Proof of PROPOSITION 4

The sign of $\frac{\partial R}{\partial N_2} = \frac{(a-c)\left\{B^2\left[N_1(\theta_2 - \theta_1) + \theta_2\right] - \frac{fb}{2}G\left[2B - (1-\theta_2)G\right]\right\}}{S_2^{\,2}}$ is ambiguous, with B,G defined in (8), f,b>0, a-c>0. Let $\Psi = \left\{B^2\left[N_1(\theta_2 - \theta_1) + \theta_2\right] - \frac{fb}{2}G\left[2B - (1-\theta_2)G\right]\right\}$, so that Sign[$dR/dN_2$]=Sign[$\Psi$]. Then:

i) The expression that multiplies B^2 and the expression that multiplies -(fb/2)G in Ψ are always positive. It follows that for f or b sufficiently large the derivative becomes negative, and thus $dR/dN_2<0$.

ii) After expanding Ψ, we get that $N_1=0$ implies $\Psi<0$, and, thus, $dR/dN_2<0$.

iii) By manipulating Ψ, and by setting fb/2 at sufficiently low values compatible with stability, i.e., $fb/2=S_2+k$, where S_2 is defined in (15) and k is a positive number approximately = 0, we find that a sufficient condition for $\Psi>0$, and thus $dR/dN_2>0$, is $\Xi \equiv N_1(\theta_2 - \theta_1)(N_2\theta_2 - N_1) + N_1\left(1 + \theta_1 - 2\theta_2 + \theta_2^2\right) + 1 - \theta_2 + \theta_2^2(N_2 - 1) < 0$. This condition becomes negative when θ_2 and N_2 are sufficiently low. It will then follow that setting f and b at sufficiently low values compatible with stability and θ_2 and N_2 at sufficiently low values, $dR/dN_2>0$.

Proof of PROPOSITION 5

$\frac{\partial R}{\partial N_1} - \frac{\partial R}{\partial N_2} = \frac{(a-c)\left[\frac{fb}{2}\frac{G^2}{B^2}(\theta_2-\theta_1)+(\theta_2-\theta_1)(N_2-1)+(\theta_2-\theta_1)-D\right]}{S_2{}^2}$, with B,D,G defined in (8),S_2 in (15), f,b>0, a-c>0, θ_2-θ_1>0. By further manipulation, we get that . $\text{Sign}\left[\frac{\partial R}{\partial N_1} - \frac{\partial R}{\partial N_2}\right] = \text{Sign } (\Delta)$ *with* $\Delta = \frac{fb}{2}G^2(\theta_2-\theta_1)+B^2[(\theta_2-\theta_1)(N_2-N_1)+1-2\theta_2]$.

To show proposition 5 we need to find that the necessary conditions for $dR/dN_2<0$ are also sufficient for dR/dN_1 - $dR/dN_2>0$. After a manipulation of Ψ (defined above in the proof of proposition 4,) we find that a necessary condition for $dR/dN_2<0$ is that $N_2>N_1+1$. By then substituting N_2 with N_1+2, its minimum value in order to have $dR/dN_2<0$, in Δ, we get $\Delta = \frac{fb}{2}G^2(\theta_2-\theta_1)+B^2[2\theta_1-1]$, which is positive for low values of θ_1, ($\theta_1 \cong 0$) or (θ_2-θ_1) sufficiently large, or a combination of the two conditions, implying that dR/dN_1 - $dR/dN_2>0$.

Proof of PROPOSITION 6

We first calculate $\frac{\partial^2 R}{\partial\theta_2\partial N_1}\Big|_{\bar{N}} = \frac{(a-c)}{S_2^3}\left(\Phi S_2 + \frac{\partial\Phi}{\partial N_1}HS_2 - 2H\Phi\frac{\partial S_2}{\partial N_1}\right)$, with a-c>0, $S_2>0$ defined in (15), Φ defined in (20) both evaluated at $N_2=N-N_1$, with N, the total number of firms, being constant; $H=N_1+1-N<0$. It can be verified that $d\Phi/dN_1$ is < 0, whereas $dR/d\theta_2<0$ implies that $\Phi>0$, by (20). It follows that a sufficient condition for $\frac{\partial^2 R}{\partial\theta_2\partial N_1}\Big|_{\bar{N}}$ >0 is $dS_2/dN_1>0$, that is always verified for (θ_2-θ_1) =0. But we have assumed that ($\theta_2>\theta_1$) , so we calculate the combination of N_1 and N that assures $dS_2/dN_1>0$ in the "worst" case scenario, i.e. $\theta_2=1$ and $\theta_1=0$. Under these conditions, we find that $N_1 > \sqrt{N-1} \Rightarrow \frac{\partial S_2}{\partial N_1} > 0$, that together with $dR/d\theta_2<0$ imply $\frac{\partial^2 R}{\partial\theta_2\partial N_1}\Big|_{\bar{N}} > 0$. But $\frac{\partial^2 R}{\partial\theta_2\partial N_2}\Big|_{\bar{N}} = -\frac{\partial^2 R}{\partial\theta_2\partial N_1}\Big|_{\bar{N}}$, so that proposition 6 follows.

APPENDIX II: VARIABLES.

A) Cost reducing R&D (R):

The CMU survey contains data on company financed R&D unit's expenditures in dollars, and the percentage of the R&D unit's effort devoted to new or improved processes. This information allows us to measure the level of cost reducing investments of the R&D units. We average this measure at the 3 and 4 SIC digit industry level.

B) Spillovers (θ_2)

Several indirect measures for spillovers among R&D performers - the parameter θ_2 in our model - can be used from the survey, but each of them seems to measure different characteristics of the spillovers variable. We then constructed a composite measure by calculating industry means of each variable and then dividing each mean by the within industry standard deviation of the variable. The spillover indicator is then sum of different standardized measures. The following variables constitute the components of the spillover measure:

- Dummy variable indicating whether the R&D unit obtained information from competitors that either suggested new R&D projects or contributed to completion of existing R&D Projects. By taking the industry mean, the variable indicates the % of R&D units that obtained useful (profitable) R&D-related information from competitors.

- Frequency with which the R&D unit obtains useful technical information about competitors activities worldwide, measured in terms of “number of contact days.”

% of process innovations for which patent protection was an effective mechanism of recoded: higher score means larger spillovers)

- % of process innovations for which “other legal mechanisms” were an effective mechanism of appropriability of returns from process innovations. (
-

appropriability of returns from process innovations. (recoded: higher score means larger spillovers.)

Number of competitors (N$_1$ $_2$)

Innovators (N). N is a self reported measure of the total number of competing innovators (able to introduce competing innovations in time to effectively diminish firms’ profits from their innovations) each

- *$_1$).* $_1$ is constructed as N-N , where N is a self reported measure of the total number of competitors the firm has worldwide. We average this variable within each industry.

Other industry level determinants.

- *Extra-industry sources of knowledge (UNIVSPIL):* Frequency with which the R&D unit obtains

measured in terms of “number of contact days.”

- *Contribution of science (SCIENCE_:* Importance of the contribution of research findings in the field
- *):*

the industry of each firm.

- *Demand growth (DEMGRW):* The change of industry sales between 1987-1992. This variable has

REFERENCES.

Arrow, K., (1962), "Economic Welfare and the Allocation of Resources for Invention", in Richard R. Nelson, ed., The Rate and Direction of Inventive Activity, Princeton University Press: Princeton.

Cohen, W.M., (1995), “Empirical Studies of Innovative Activity,” in Paul Stoneman, ed., Handbook of the Economics of Innovation and Technological Change, Basil Blackwell: Oxford.

Cohen, W.M. and Klepper, S., (1992), "The Anatomy of Industry R&D Intensity Distributions", American Economic Review, Vol. 82, pp. 773-88.

Cohen, W.M. and Levinthal, D.A., (1989), "Innovation and Learning: the Two Faces of R&D", Economic Journal, Vol. 99, pp. 569-596.

Cohen, W.M. and Levinthal, D.A., (1990), "Absorptive Capacity: A New Perspective on Learning and Innovation," Administrative Science Quarterly, Vol. 35, pp. 128-152.

Cohen, W.M., Nelson, R.R., and Walsh, J., (1997), “Appropriability Conditions and Why Firms Patent and Why They Do Not in the American Manufacturing Sector,” Carnegie Mellon University, Mimeo.

D’Aspremont, C., and A. Jacquemin, (1988), “Cooperative and Noncooperative R&D in Duopoly with Spillovers,” American Economic Review, Vol. 78, pp. 1133-1137.

De Bondt, R., (1996), “Spillovers and Innovative Activities,” International Journal of Industrial Organization, Vol. 15, pp.1-28.

De Bondt, R., Slaets, PP., and Cassiman B., (1992), “The Degree of Spillovers and the Number of Rivals for Maximum Effective R&D,” International Journal of Industrial Organization, Vol. 10, pp.35-54.

Dixit, Avinash, (1986), "Comparative Statics for Oligopoly," International Economic Review, Vol. 27, pp. 107-22.

Griliches, Zvi, (1995), “R&D and Productivity: Econometric Results and Measurement Issues,” in Paul Stoneman, ed., Handbook of the Economics of Innovation and Technological Change, Basil Blackwell: Oxford.

Hahn, Frank H., (1962), "The Stability of the Cournot Oligopoly Solution," Review of Economic Studies, Vol. 29, pp.329-31.

Kamien, M., Muller, E., and I. Zang, (1992), “Research Joint Ventures and R&D Cartels,” American Economic Review, Vol. 82, pp. 1293-1306.

Klepper, Steven, (1996) “Entry, exit, growth, and innovation over the product life cycle,” American Economic Review, Vol. 86, pp. 562-583.

Leahy, D. and Neary, PP., (1997), "Public Policy Towards R&D in Oligopolistic Industries," ______________________, Vol. 87, pp. 642-662.

Levin, R.C., (1988), “Appropriability, R&D Spending, and Technological Performance,” __________________________________, Vol. 78, pp. 424-428.

Levin, R.C.,
Returns from Industrial Research and Development,” Brookings Papers on Economic ______, n. 3, pp. 783-820.

Levin, R.C. and Reiss, PP.C., (1988), “Cost Reducing and Demand Creating R&D with
Rand Journal of Economics, Vol. 19, pp.538-556.

Industrial Research in American Manufacturing, 1900-1940", Explorations in Economic ______, October.

Spence, A.M., (1984), “Cost Reduction, Competition, and Industry Performance,” ___________, Vol. 52, pp. 101-121.

White, H., (1980), “A Heteroscedasticity-Consistent Covariance Matrix Estimator and a
Econometrica, Vol. 48, pp. 817-838.