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# Innovation, Firm Size, and RDSearch

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## *Abstract*

We present evidence that small firms perform two to four times more innovations per dollar of RDthan large firms. We propose a search theory of RDthat accounts for the evidence. A firm incurs RDexpenses until it has discovered a level of RDproductivity that is sufficiently great to warrant stopping the search. We show that because the large number of RDprojects run by a large firm becomes a substitute for enhanced RDproductivity, the average RDproductivity of a firm is decreasing in firm size.

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## 1. INTRODUCTION

Since the writings of Schumpeter (1950), economists have been interested in the relationship between a firm's size and the rate at which it innovates. Various theoretical arguments have been put forth supporting Schumpeter's hypothesis that *large* firms should be more innovative [Cohen, Levin, and Mowery (1987)]. Due to capital market imperfections, large firms may have superior access to financing of R&D projects, because size is correlated with the availability and stability of internally generated funds. If this is the case, large firms have a comparative advantage since R&D may involve significant start-up costs and economies of scale and scope. Complementarities between R&D and non-manufacturing activities, such as marketing, sales, and distribution, may be better developed within large firms. The larger is a firm, the greater is the return to reducing its (marginal) cost of production by engaging in process innovations [Cohen and Klepper (1996b)]. Finally, large firms spread the risks of R&D by holding diversified portfolios, and so may invest in more risky projects, which typically earn a higher return [Holmstrom (1989)].

With such theoretical arguments in favor of Schumpeter's hypothesis, it seems paradoxical the exact opposite has been verified empirically. Specifically, within industries, the number of innovations per dollar of R&D *decreases* with firm size, and smaller firms account for a disproportionately large number of innovations relative to their size [Cohen and Klepper (1996a), Bound et al (1984), Acs and Audretsch (1988, 1991a), Pavitt et al (1987)], though this is not true in all industries [Acs and Audretsch (1987)]. For example, Acs and Audretsch (1991b) find that small firms contribute 2.4 times more innovations per employee than do large firms. Most studies use patent counts as the measure of innovative output, but patents differ greatly in their economic impact. Trajtenberg (1990) and Hall, Jaffe, and Trajtenberg (2005) argue that citations (i.e. the number of times a patent has been cited in future patent filings) are an accurate metric of a patent's relative importance.

We perform a firm-level study utilizing patent citations data from the NBER. We examine patents applied for in 1976 and observe their citations over 1976-2002. We obtain two findings. First, small firms receive two times more patent citations (and four times more patent counts) per dollar of R&D than large firms. Second, there are decreasing returns to R&D irrespective of whether innovative output is measured using patent counts or citations. Cohen, Levin, and Mowery argue that the business unit, and not overall firm, is the appropriate empirical metric of size in a research organization. If so, then the above-mentioned benefits to being a large firm are irrelevant, since they do not apply to a business unit, but rather its corporate parent. Thus, we are faced with the question originally posed by Scherer (1984, Ch. 11): why should *small* firms be more innovative?

This paper proposes a search theory of R&D that accounts for the evidence. Research is a process in which a firm incurs R&D expenses until it has discovered a level of R&D productivity that is sufficiently great to warrant stopping the search. A large firm runs multiple R&D projects, while being subject to decreasing returns to size (because not all R&D projects come to fruition) and decreasing returns to R&D (in accord with our evidence). Every period, the firm receives a new draw of R&D productivity, and decides whether to adopt the current set of innovations or prolong the search. We show that the average R&D productivity of a firm is decreasing in firm size because the large number of R&D projects run by a large firm becomes a substitute for enhanced R&D productivity; and the average number of innovations per dollar of R&D is decreasing in firm size since small firms search sufficiently long to discover a high level of R&D productivity.

The paper is organized as follows. Section 2 presents the evidence relating firm size and the rate of innovation. Section 3 presents the search model of R&D. Section 4 concludes.

## 2. THE EVIDENCE

To determine the relationship between a firm's size and its rate of innovation, we utilize the NBER patent citations dataset from Hall, Jaffe, and Trajtenberg (2001), hereby referred to as HJT, which has since been updated. Covering all U.S. manufacturing industries, HJT matched the number of citations received during the period 1976-2002 by patents applied for since 1965. We exclusively consider patents applied for in 1976, the first year with citation observations, since citations occur for many years thereafter. HJT constructed a variable termed "R&D stock" which is a cumulative sum of R&D expenditures going back to 1965, applying a depreciation rate of 15 percent. By employing the stock variable instead of contemporaneous R&D expenditures, we allow for the possibility that patents applied for in 1976 were the result of earlier research. In the HJT dataset, firms are assigned to one of six broadly-defined sectors. We obtain the 2-digit SIC code corresponding to each firm by merging the HJT dataset with Compustat. The sample includes 1,481 firms that applied for a total of 18,179 patents in 1976 that obtained 150,965 citations during 1976-2002.

The median R&D stock is 3.37 million 1976 dollars, which splits the sample into "small" and "large" firms. Table 1 contains the mean, standard deviation, and maximum of the number of patents and citations per dollar of R&D stock. Small firms obtain on average 5.32 citations per dollar of R&D stock, whereas large firms obtain on average only 2.69. That is, small firms are 1.98 times more productive at R&D holding the size of the research input constant. Using patent counts instead of citations, they are 3.97 times more productive.

We estimate two separate negative binomial MLE models with 2-digit industry dummies (which takes into account the fact that the dependent variable is a count variable). The two dependent variables are patent counts and citations; and in both cases, the independent variable is the log of R&D stock, thus observations with zero R&D stock are excluded. Table 2 contains the results. When the dependent variable is patent counts, the elasticity of the R&D stock is 0.73. When citations are used instead, the elasticity rises to 0.89. In both cases, the estimates are significant at the 1% level, and Wald tests reject the null hypothesis of constant returns to R&D.

To summarize, small firms are between two to four times more innovative per dollar of R&D than large firms, and there are decreasing returns to R&D irrespective of whether innovative output is measured using patent counts or citations, the latter of which adjusts for varying patent quality. With few exceptions, previous empirical studies also obtain decreasing returns to R&D, which has been argued is the cause of the observed relationship between firm size and the rate of innovation. However, we show that decreasing returns to R&D alone is not sufficient to explain the evidence that small firms are more innovative per dollar of R&D than large firms. There must be another mechanism at work, which this paper argues stems from the search process of R&D.

## 3. THE MODEL

There is a continuum of firms that differ exogenously in their size $S$ (which may be an indicator of manufacturing efficiency or managerial ability, for example). A firm of size $S$ runs $S$ R&D projects searching for a collection of new products or processes, incurring the R&D expense $R$ per project. $R$ thus represents R&D expenditures at the business unit level, such that $SR$ is R&D expenditures at the corporate level. The firm invents $N = AS^{1-\alpha}R^{\alpha}$ new products, where $A$ denotes the R&D productivity of the firm and $\alpha \in (0,1)$ reflects the extent to which innovation is R&D-intensive. There are decreasing returns to firm size because not all R&D projects come to fruition; and decreasing returns to R&D. Let $\pi$ denote the (exogenous) payoff per innovation, which is independent of firm size *S* so as to not bias the results a priori. Let $n = N/(SR) = A/(S^{\alpha} R^{1-\alpha})$ denote the number of innovations per dollar of (total) R&D. Our goal is to prove that *n* is decreasing in firm size *S*, in accord with our evidence.

We first show that in the absence of a search component, this simple framework predicts that firm size *S* and the number of innovations per dollar of R&D *n* are uncorrelated. The firm solves $\max_R \pi A S^{1-\alpha} R^{\alpha} - SR$, yielding the R&D policy (per project) $R = (\alpha \pi A / S^{\alpha})^{1/(1-\alpha)}$. The number of innovations per dollar of R&D is thus $n = 1/(\alpha\pi)$, which is independent of firm size *S*, and thereby counterfactual. Furthermore, R&D expenditures at the business unit level *R* are decreasing in *S*, which is inconsistent with evidence that firm size and R&D expenditures at all levels are positively correlated [Bound et al (1984)].

Consider instead a dynamic version of the model, wherein the firm searches for a sufficiently high level of R&D productivity, after which it adopts (or performs) the innovations. At the beginning of every period, the firm observes the realization of an idiosyncratic i.i.d. R&D productivity shock $A \in [0, \infty)$ drawn from the distribution *F*. So as to not bias the results a priori, the distribution *F* is independent of firm size *S*, thus all firms irrespective of size face the same technological opportunities to innovate. Let $\beta \in (0,1)$ denote the discount factor of the firm, and $V(A)$ the value function of the firm when the realized R&D productivity is *A*. The firm decides every period whether to adopt or reject the current set of innovations:

(1) $V(A) = \max\{\pi A S^{1-\alpha} R^{\alpha}, -SR + \beta \int_0^{\infty} V(A') dF(A')\}$ .

The search policy consists of a stopping rule described by the cutoff $\hat{A}(R;S)$. If the current R&D productivity exceeds $\hat{A}(R;S)$, then the current set of innovations are adopted. Let *EV* denote the firm's expected value. The cutoff is the R&D productivity at which the firm is indifferent between adopting versus rejecting:

(2) $\pi \hat{A}(R;S) S^{1-\alpha} R^{\alpha} = -SR + \beta EV$ .

The expected value of the firm thus satisfies:

(3) $EV = \int_0^{\hat{A}(R;S)} (-SR + \beta EV) dF(A) + \int_{\hat{A}(R;S)}^{\infty} \pi A S^{1-\alpha} R^{\alpha} dF(A)$ .

Combining (2) and (3) we infer

(4) $S^{\alpha} R^{1-\alpha} / \pi = \beta \int_{\hat{A}(R;S)}^{\infty} A dF(A) - \hat{A}(R;S)[1 - \beta F(\hat{A}(R;S))]$ .

This expression implicitly defines the cutoff $\hat{A}(R;S)$ .

Let $\mu(R;S) \equiv [1 - F(\hat{A}(R;S))]^{-1} \int_{\hat{A}(R;S)}^{\infty} A dF(A)$ denote the average R&D productivity, which is increasing in $\hat{A}(R;S)$. We prove in the Appendix that $\mu(R;S)$ has the following properties:

**PROPOSITION 1:** Taking as given the level of R&D expenditures (per project) $R$, the average R&D productivity $\mu(R;S)$ is decreasing in $R$ and firm size $S$.

The R&D investment (per project) $R$ can be interpreted as a typical search cost: the greater is $R$, the less willing is the firm to continue searching (i.e. the less stringent is the firm's stopping policy), lowering the average R&D productivity. Note, however, that decreasing returns to R&D are required for this effect to occur.

Small firms adopt innovations with a greater R&D productivity. A large firm runs a large number of R&D projects, but not all projects are successful due to the inherent uncertainty associated with R&D, generating decreasing returns to size. The large number of R&D projects thereby becomes a substitute for enhanced productivity.

The firm chooses R&D expenditures (per project) $R$ so as to maximize its expected value $EV$. We infer from (2) that a firm of size $S$ has the expected value

(5) $EV = (S/\beta)[R + \pi(R/S)^{\alpha}\hat{A}(R;S)]$.

Maximizing (5) with respect to $R$, we obtain the first-order condition (FOC)

(6) $1 + (\pi / S^{\alpha}) d[R(S)^{\alpha}\hat{A}(R(S);S)]/dR = 0$.

This expression implicitly defines the optimal R&D policy (per project) $R(S)$. We prove in the Appendix that large firms perform more R&D per project:

**LEMMA 1:** The optimal R&D expenditures (per project) $R(S)$ of the firm are increasing in firm size $S$.

There is complementarity in the innovation production function between firm size and R&D; moreover, there are decreasing returns to firm size (since not all R&D projects come to fruition). It follows that large firms have a stronger incentive to invest in R&D, in accord with existing theories of R&D, such as Klepper (1996). There is ample evidence that firm size and R&D expenditures (at the business unit or corporate level) are positively correlated. In a regression of log R&D expenditures against log sales (with industry dummies), Bound et al (1984) obtained a significant coefficient of 0.965.

Define $\mu(S) \equiv [1 - F(\hat{A}(R(S);S))]^{-1} \int_{\hat{A}(R(S);S)}^{\infty} A\,dF(A)$ as the average R&D productivity, taking into account the optimal R&D policy, which satisfies:

**PROPOSITION 2:** Suppose the R&D policy is optimal. The average R&D productivity $\mu(S)$ is decreasing in firm size $S$.

There are two forces contributing towards the relationship between average R&D productivity $\mu(S)$ and firm size, both of which operate in the same direction. Because $\mu(S)$ is increasing in the cutoff rule $\hat{A}(R(S);S)$, to determine its properties, we calculate the total derivative of the cutoff with respect to firm size:

(7) $\dfrac{d\hat{A}(R(S);S)}{dS} = \dfrac{\partial\hat{A}(R(S);S)}{\partial S} + \dfrac{\partial\hat{A}(R(S);S)}{\partial R}\dfrac{dR(S)}{dS}$.

We label the first term on the right-hand side (RHS) the *size* effect. We proved in Proposition 1 that $\partial\hat{A}(R;S)/\partial S < 0$: taking as given the R&D search cost *R*, a large firm searches for a relatively short period of time, planning to adopt a low level of R&D productivity, because the large number of projects becomes a substitute for enhanced productivity. We label the second term on the RHS the *R&D* effect, which represents the contribution of the optimal R&D policy. We proved in Lemma 1 that large firms perform more R&D per project, i.e. $dR(S)/dS > 0$, due to the complementarity that exists between firm size and R&D. Finally, from Proposition 1, we have that $\partial\hat{A}(R;S)/\partial R < 0$: the smaller is the R&D search cost, the longer a firm is willing to search for a high level of R&D productivity. We infer that both the size and R&D effects operate in the same direction, such that small firms adopt innovations with a greater R&D productivity, i.e. $d\hat{A}(R(S);S)/dS < 0$.

Our main finding is that small firms are more innovative than large firms, in accord with the evidence. The number of innovations per dollar of (total) R&D is $n(S) = A/(S^{\alpha}R(S)^{1-\alpha})$, which has the average $\bar{n}(S) = \mu(S)/(S^{\alpha}R(S)^{1-\alpha})$ with these properties:

**PROPOSITION 3:** Suppose the R&D policy is optimal. The average number of innovations per dollar of (total) R&D $\bar{n}(S)$ is decreasing in firm size *S*.

There are three forces contributing towards the relationship between the average number of innovations per dollar of (total) R&D and firm size, all of which operate in the same direction. Take the total derivative of $\bar{n}(S) = \mu(S)/(S^{\alpha}R(S)^{1-\alpha})$ with respect to *S*, to obtain

(8) $$\frac{S}{\bar{n}(S)}\frac{d\bar{n}(S)}{dS} = \frac{S}{\mu(S)}\frac{d\mu(S)}{dS} - \alpha - (1-\alpha)\frac{S}{R(S)}\frac{dR(S)}{dS}.$$

First, there is the *R&D productivity* effect. Proposition 2 showed that the average R&D productivity $\mu(S)$ is decreasing in firm size *S*, thus the contribution of the R&D productivity effect is negative. Second, there is the *size* effect. Because there are decreasing returns to size in the innovation production function (since not all R&D projects come to fruition), large firms obtain proportionally fewer innovations per dollar of (total) R&D. Third, there is the *R&D* effect. Since there are decreasing returns to R&D in the innovation production function, firms that perform more R&D (per project) obtain proportionally fewer innovations per dollar of (total) R&D; moreover, Lemma 1 showed that large firms perform more R&D, $dR(S)/dS > 0$.

## 4. CONCLUSION

We provided empirical evidence that small firms are more innovative per dollar of R&D than large firms; yet, with few exceptions, existing theories predict otherwise. We showed that a naïve model of R&D predicts the number of innovations per dollar is independent of firm size, which is counterfactual. We then proposed a partial equilibrium search model of R&D that, though highly stylized, captures the salient features of R&D. Firms perform R&D until they discover a sufficiently great level of R&D productivity that warrants stopping the search. Assuming there are decreasing returns to R&D and firm size in the innovation production function, we found that large firms use their large number of R&D projects as a substitute for productivity; as such, small firms search long enough to discover a high level of R&D productivity that compensates for their small size.

From an empirical standpoint, a shortcoming of this paper is that we are unable to test the prediction that large firms innovate more frequently than small firms. Because we observe empirically that small firms have a greater level of R&D productivity, in a theoretical search context, this necessarily implies that small firms innovate less frequently, but the data may show otherwise. Future empirical work should correlate the rate of innovation with firm size.

The issue of firm size and innovation is of interest from a policy perspective because current doctrine is geared towards subsidizing large R&D investments initiated by large firms. Our model provides a rationale for the (flawed) policy of subsidizing large R&D investments. Because small firms search sufficiently long to adopt innovations with a high level of R&D productivity, large firms innovate more frequently than small firms. This may be misconstrued as implying that large firms are more effective at performing R&D, when in fact they have a low level of R&D productivity.

We argue in favor of a policy shift towards the subsidization of small R&D investments since R&D achieves its highest return in small firms and small firms have greater difficulty in obtaining R&D funding from financial institutions (due to capital market imperfections). The potential benefit is significant since innovation is an engine of growth.

## REFERENCES


Acs, Zoltan J., and David B. Audretsch (1987). "Innovation, Market Structure, and Firm Size," *Review of Economics and Statistics*, Vol. 69, No. 4, pp. 567-74.

Acs, Zoltan J. and David B. Audretsch (1988). "Innovation in Large and Small Firms," *American Economic Review*, Vol. 78, pp. 678-90.

Acs, Zoltan J. and David B. Audretsch (1991a). "R&D, Firm Size, and Innovative Activity", in Zoltan J. Acs and David B. Audretsch, eds., *Innovation and Technological Change: An International Comparison*, New York, NY: Harvester Wheatsheaf.

Acs, Zoltan J. and David B. Audretsch (1991b). "Innovation and Technological Change: An Overview", in Zoltan J. Acs and David B. Audretsch, eds., *Innovation and Technological Change: An International Comparison*, New York: Harvester Wheatsheaf.

Bound, John, Clint Cummins, Zvi Griliches, Bronwyn Hall, and Adam Jaffe (1984). "Who Does R&D and Who Patents?" in Zvi Griliches, ed., *R&D, Patents, and Productivity*, Chicago, IL: University of Chicago Press.

Cohen, Wesley M., and Steven Klepper (1996a). "A Reprise of Size and R&D," *Economic Journal* 106, 925-51.

Cohen, Wesley M. and Steven Klepper (1996b). "Firm Size and the Nature of Innovation Within Industries: The Case of Process and Product R&D," *Review of Economics and Statistics*, Vol. 78 (2), May, pp. 232-43.

Cohen, Wesley M., Richard C. Levin, and David Mowery (1987). "Firm Size and R&D Intensity: A Re-Examination," *Journal of Industrial Economics* 35, 543-63.

Hall, Bronwyn H., Adam Jaffe, and Manuel Trajtenberg (2001). "The NBER Patent Citation File: Lessons, Insights, and Methodological Tools," *NBER Working Paper* No. 8498.

Hall, Bronwyn H., Adam Jaffe, and Manuel Trajtenberg (2005). "Market Value and Patent Citations," *RAND Journal of Economics*, Vol. 36, No. 1, pp. 16-38.

Holmstrom, Bengt (1989). "Agency Costs and Innovation," *Journal of Economic Behavior and Organization* 12, 305-27.

Klepper, Steven (1996). "Entry, Exit, Growth, and Innovation over the Product Life Cycle," *American Economic Review*, Vol. 86, No. 3, pp. 562-83.

Scherer, Frederic M. (1984). *Innovation and Growth: Schumpeterian Perspectives*. Cambridge, MA: MIT Press.
Schumpeter, Joseph (1950). *Capitalism, Socialism, and Democracy*. 3rd Edition. New York, NY: Harper and Row.
Trajtenberg, Manuel (1990). "A Penny for Your Quotes: Patent Citations and the Value of Innovations," *RAND Journal of Economics*, Vol. 21, pp. 172-87.

## APPENDIX

**Proof of Proposition 1:** The derivative of the right-hand side (RHS) of (4) with respect to $\hat{A}$ is $\beta F(\hat{A})-1$, which is negative, implying the RHS of (4) is strictly decreasing in $\hat{A}$, such that the cutoff is uniquely defined. The left-hand side (LHS) of (4) is increasing in *R* and *S*, yielding the results $\partial\hat{A}(R;S)/\partial S<0$ and $\partial\hat{A}(R;S)/\partial R<0$.

**Proof of Lemma 1:** The second-order condition (SOC) of the firm's problem is $d^2[R^\alpha\hat{A}(R;S)]/dR^2<0$. Taking the total derivative of the FOC (6) with respect to *S*, we obtain

(A.1) $-\alpha S^{-(1+\alpha)}d[R^\alpha\hat{A}(R;S)]/dR+S^{-\alpha}(dR/dS)d^2[R^\alpha\hat{A}(R;S)]/dR^2=0$.

From the FOC, we have $d[R^\alpha\hat{A}(R;S)]/dR=-S^\alpha/\pi$. Applying this expression to (A.1), the latter becomes $dR/dS=-(\alpha/\pi)\{S^{1-\alpha}d^2[R^\alpha\hat{A}(R;S)]/dR^2\}^{-1}$. From the SOC, we conclude $dR/dS>0$.

## TABLES

**Table 1: Research Productivity by Firm Size Class**

| Variable | Firm Size | Mean | Std Dev | Max |
|---|---|---|---|---|
| Citations/R&D Stock | R&D Stock < Median | 5.32 | 25.03 | 395.83 |
| | R&D Stock > Median | 2.69 | 4.42 | 46.58 |
| | Ratio small/large | 1.98 | 5.66 | 8.50 |
| | | | | |
| Patents/R&D Stock | R&D Stock < Median | 1.51 | 8.00 | 200.00 |
| | R&D Stock > Median | 0.38 | 0.52 | 5.89 |
| | Ratio small/large | 3.97 | 15.38 | 33.96 |

Notes: "Citations" are total citations received 1976-2002 from patents applied for in 1976; "Patents" are the number of patents applied for in 1976 that were later granted; "R&D Stock" is the discounted sum of R&D expenditures 1965-1976 in 1976 millions; the dataset is from Hall, Jaffe, and Trajtenberg (2001) and Compustat.

**Table 2: Negative Binomial MLE Estimates**

| | (1) Patents | (2) Citations |
|---|---|---|
| Log R&D Stock | 0.7287* | 0.8880* |
| | (0.0171) | (0.0332) |
| | | |
| Log Likelihood | 61,750 | 885,657 |

| | | |
|---|---|---|
| Observations | 1,481 | 1,481 |

Notes: standard errors are in parentheses; * = significant at the 1% level; both equations include 2-digit industry dummies; “Citations” are total citations received 1976-2002 from patents applied for in 1976; “Patents” are the number of patents applied for in 1976 that were later granted; “R&D Stock” is the discounted sum of R&D expenditures 1965-1976 in 1976 millions; the dataset is from Hall, Jaffe, and Trajtenberg (2001) and Compustat.