The Democratization of U.S. Research and Development after 1980

Robert M. Hunt
Leonard I. Nakamura[1]

Research Department,
Federal Reserve Bank of Philadelphia

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Abstract

Using Compustat data, we document that prior to 1980, large R&D performing firms had higher R&D intensity (R&D/Sales) than small firms in the same industries. Over the course of the next two decades, in these same industries, small firms came to rival and even surpass large firms in terms of R&D intensity. During this period, corporate R&D intensity nearly doubled and most of the aggregate increase is due to the substantial increase in R&D intensity among small firms. Little of the change in composition is explained by changes in the industrial distribution of R&D.

Why did small firms increase their R&D after 1980 and not before? We argue that, after 1980, small firms were able to compete on better terms in industries already dominated by large firms. We show that the patterns we observe in the data are consistent with a straightforward dynamic model of R&D with falling barriers to entry.

But what barriers fell? We argue the shift in R&D intensity by small firms was largely due to the electronics revolution. Prior to the 1980s, a large corporate sales and clerical force was an essential factor for the rapid and widespread distribution of new products. This technology clearly favored large, established firms. But the electronics revolution obviated the need for these factors, making entry easier.

[1] Research Department, Federal Reserve Bank of Philadelphia, Ten Independence Mall, Philadelphia, PA 19106.

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1. Introduction

Beginning around 1980, the personal computer made computation accessible to small firms and firm investment in computers increased sharply. The change in scale made possible by the microprocessor, we shall argue, reduced barriers to entry and enabled small firms to become more important contributors to U.S. research and development (R&D).

Until 1980, large economic actors – the federal government and large firms – dominated research and development in the United States. Figure 1, which shows spending on research and development by source relative to gross domestic product, illustrates that most of U.S. R&D was being funded by the federal government before the 1980s. The share of corporate-funded R&D rose from the mid-1960s, but that was primarily because federal R&D was falling. Indeed, between 1969-79, corporate R&D barely kept pace with GDP; since then it has grown considerably more rapidly.

Why did this acceleration occur? The answer is the growth in R&D conducted by smaller firms. In 1980, firms with 5,000 or fewer employees accounted for only 15 percent of U.S. corporate R&D. This share has grown over time. Over the course of the next two decades the ratio of U.S. corporate R&D to GDP nearly doubled, but almost all of the increase was accounted for by smaller firms (Figure 2). Why did small firms increase their R&D after 1980? We argue that, to a substantial extent, it was because small firms were better able to compete in new product markets.

Using Compustat data, we document that prior to 1980, large R&D performing firms (measured in employees and in revenues) had higher R&D intensity (as measured by R&D divided by sales or operating expenses) than small firms in the same industries. Over the course of the next two decades, in these same industries, small firms came to rival and even surpass large firms in terms of R&D intensity.

We point out that in the Compustat data, R&D remained highly concentrated in 49 (three digit SIC) industries.[1] Indeed the concentration increased rather than dispersed, despite the fact that the proportion of all firms conducting R&D has risen. In 1974, 83 percent of R&D was performed in these industries; in 1999 they accounted for 92 percent of R&D.

Indeed, most of the R&D in these industries was performed by very large firms—firms with 25 thousand or more employees. These long-term incumbent firms were protected by barriers to entry into product markets according to Chandler (1994). These barriers were the result of large-scale investments in a corporate structure whose core purpose was information processing: the sales and administrative staff. This staff in turn enabled the long-term incumbent to sell new products in sufficient volume to justify large investments in new product development.

[1] Our analysis (below) relies on even finer industry definitions, but the conclusion is the same.

The PC revolution, by accelerating the automation of information processing, made it possible for relatively small firms to quickly transact large volumes of new products since, for the first time, they were able to automate business information processing.[2] Its empirical counterpart was an increase in the economic resources devoted to investments in computers and peripheral equipment, as measured by its ratio to GDP in nominal terms.

The electronics revolution also reduced the cost of performing R&D. We use a simple model to differentiate the effects of different types of reductions in the cost of innovation. Our empirical work then examines the effect of computerization on the responsiveness of own R&D to the R&D of rivals, and on the market value of R&D. We also differentiate across industries and firms by separating out long-term incumbent firms by size: we examine firms that had more than 25 thousand employees in 1965 and their industries to analyze how the presence of these firms influenced the nature of competition.

We are able to show that computerization increased spillovers between firms and their rivals, so that firms did more R&D in the year following increases in rivals' R&D. We also show that computerization meant that increases in rivals' R&D generally reduced own market value. However, long-term incumbents react particularly strongly to rivals' R&D and are able to preserve more of the value of their own R&D as a consequence.

1.1. Related Literature

The literature that relates rivals' R&D to own firm R&D and to various measures of output (such as market value) dates back to the 1970s and includes, for example, Grabowski and Baxter (1973), Bernstein and Nadiri (1989), and Cockburn and Henderson (1994).

The empirical paper most closely related to our work is Bloom et al. (2005). They explain movements in firm R&D and market value with regressors constructed by aggregating rivals' R&D two ways: using weights of technological-relatedness of the firms (measured by the technology classes of firm patents) and weights of market-relatedness (measured by the SIC codes of product market segments) to identify technology spillovers and product market rivalry. Their striking result is that technologically related rivals' R&D increases market value, while market-related rivals' R&D reduces market value. They also find that both types of rivals' R&D increases own R&D. Our interest is in how R&D spillovers and outcomes change as a consequence of computerization. We interact computerization over time with rivals' R&D.

Another long and active strand of research has related industry structures to research and development. Recently this work has looked to competitive policy reforms to identify exogenous changes in product market competition;

[2] The development of the personal computer was only one facet of the effects of the development of the decentralization of information processing in the late 1970s and early 1980s. Video terminals, for example, made computer timesharing more practical. Scanners and electronic cash registers automated the input of electronic data.

the paper by Aghion et al. (2002) is a good example. They find that there is an inverted U-shaped relationship between product market competition, as measured by price-cost margins, and innovation, as measured by patenting activities.

The third literature to which our paper relates discusses how the economy has changed since the late 1970s. In general, these papers suggest that the number of new products increased, entry occurred, and volatility and risk experienced by firms rose. Bils and Klenow (2001) argue that product variety accelerated after 1980. The value of R&D fell in the late 1980s (Hall, 1993). The stock market value of an older generation of firms fell (Greenwood and Jovanovic, 1999) and a new generation of firms arose (Jovanovic and Rousseau, 2001). Idiosyncratic firm risk rose beginning in 1980 as measured by stock market valuations (Campbell et al., 2001, and Comin and Philippon, 2005), while corporate CEOs' tenure became shakier (Huson, et al., 2001.) All these papers are consistent with the notion that R&D competition intensified, which is what we explore.

1.2. Marketing Capital as a Barrier to Entry

In this paper we set forth a model in which established firms initially have an advantage in investing in new product development because of its past investment in a customer base, which we call marketing capital. This model is a simplification of Stein (1997). Our model varies from Stein in that we focus on the impact of a decline in the cost of this investment; the personal computer revolution in the late 1970s is modeled as a decrease in the price of marketing capital

There are two firms, an incumbent that currently monopolizes the market and a potential entrant. Either or both may choose to engage in risky R&D. Successful innovations are drastic; that is, they entirely displace the existing product in the market. If the incumbent successfully innovates, it implements the superior technology and earns additional profits. If the entrant successfully innovates, before it can enter the market, it must first invest a lump-sum in order to establish its own customer base. If both firms successfully innovate, and the entrant sinks its investment in marketing capital, the two firms will compete in prices. In equilibrium, the entrant would never choose to do so, as it could not amortize the cost of R&D or its marketing capital. Entry, then, is observed only where the entrant is the only successful innovator, and the associated rents are sufficiently large.

The likelihood of success for the entrant depends on the research intensity of the incumbent, which reduces the probability of successful entry. Conversely, the research intensity of the entrant influences how much weight the incumbent places on its current profit stream when determining how much it should invest in an innovation that will displace what it already has. We examine the behavior of the incumbent and potential entrant as we vary the magnitude of the cost of marketing capital. We show that the entrant is more likely to invest in R&D and enter the market, as the cost of marketing capital falls relative to the profits currently earned by the incumbent. Thus the model suggests an unambiguous hypothesis about the behavior of new firms as the cost of deploying complementary assets falls.

The effect of such changes on the behavior of incumbents is more complicated. We show that the incumbent will invest either more or less in R&D than the entrant. When the cost of new marketing capital exceeds the current rents enjoyed by the incumbent, the entrant does not engage in R&D. There is no interaction, and the model is the standard monopoly problem.

As the cost of marketing capital is reduced, the entrant will eventually find it worthwhile to engage in R&D. This has the effect of increasing the incumbent's incentive to engage in R&D as the replacement motive is diminished and greater incumbent R&D reduces the entry incentive. Still, as the cost of marketing capital continues to fall, the entrant will perform more and more R&D, eventually doing more R&D than the incumbent if current profits are sufficiently high.

We argue that the predictions of the model are observed in the data. After 1980, smaller and newer firms became more research intensive in both absolute terms and relative to larger or older firms. Incumbents also raised their research intensity. Of course, a variety of other factors might explain these changing patterns in R&D investments.

2. A Simple Model of R&D with Marketing Capital

There are two firms: an incumbent (i) and a potential entrant (e).[3] At the beginning of the game, the incumbent is the only active producer and earns a monopoly profit $\pi > 0$. Both firms have access to a common stochastic R&D technology. Firm j chooses a probability of success θ^j, which costs $-rLn(1-\theta^j)$, where r is the price of R&D relative to final output. Firms chose their R&D simultaneously, taking their rival's strategy as given. Nature then determines the success or failure of the firms' R&D programs (we assume these draws are independent). A successful innovation results in a new level of profits $\tilde{\pi} > \pi$, gross of R&D costs. This innovation is drastic; i.e., the new product drives the old one completely out of the market. In order to produce, a successfully innovating entrant must then sink $b > 0$ to establish its distribution network. If both firms successfully invent, and the entrant sinks b, they compete in prices, resulting in zero gross profits. Of course, that would not be an equilibrium outcome of the game.

[3]In the appendix, we generalize the model to allow for more than one firm to enter the market.

2.1. Equilibrium Outcomes

The objective functions of the entrant and incumbent, respectively, are simply

$$\underset{\theta^e \in [0,1]}{Max} \left\{ V^e = \theta^e(1-\theta^i)[\tilde{\pi} \ - b] + rLn(1-\theta^e), 0 \right\} \text{ and}$$

$$\underset{\theta^i \in [0,1]}{Max} \left\{ V^i = \theta^i \tilde{\pi} + (1-\theta^i)(1-\theta^e)\pi + rLn(1-\theta^i), (1-\theta^e)\pi \right\}.$$

Assuming an interior equilibrium, the first order conditions imply the following R&D reaction functions for these firms:

$$\hat{\theta}^e = 1 - \frac{r}{(1-\theta^i_e)[\tilde{\pi} \ - b]} \qquad \text{and} \qquad \hat{\theta}^i = 1 - \frac{r}{\tilde{\pi} \ - (1-\theta^e)\pi}.$$

It is readily apparent that the reaction function for the entrant is downward sloping, while it is upward sloping for the incumbent. This makes it possible for an incumbent to discourage entry, and the probability of being displaced, as long as it has sufficient incentive to do R&D (see below).[4] In our empirical estimation, we expect the slope of the entrant's reaction function to be smaller, at least initially, than the one for the incumbent.

An *interior* equilibrium does not exist for all possible combinations of the exogenous parameters $(\pi, \tilde{\pi}, r, b)$. The various possibilities are depicted in Figure 3, which collapses the parameter space into two dimensions (π, b) relative to $\tilde{\pi}$ and reports the closed-form values of the firms' R&D.

In general, the most R&D is observed for small values of π and b (the lower left portion of the parameter space). The least amount of R&D is observed for higher values of π and b (the upper right portion of the parameter space). For example, the entrant will never do R&D if there are insufficient profits to amortize both R&D and the cost of marketing capital, i.e., where $\tilde{\pi} \ -b - r \leq 0$ (region I and the upper portion of region II). Similarly, the incumbent will not do any R&D if it costs more than the incremental gain in profits if successful, i.e. where $\tilde{\pi} \ -\pi - r \leq 0$ (also region I). In addition, whenever the incumbent's existing rents are less than the cost of marketing capital for the entrant, the incumbent will always do enough R&D to deter entry (the lower portion of region II). Region IV characterizes the opposite possibility: where b is sufficiently small, and π is sufficiently large, entry is assured and the incumbent chooses not to engage in R&D.[5] In region III, both the incumbent and entrant engage in R&D. This region can be divided into subregions of the parameter space where the incumbent does more R&D than the entrant and where the opposite is true.[6]

[4] It is easy to verify that in markets characterized by two symmetric incumbents (or entrants) the reaction functions of both firms are upward sloping.

[5] Note that in Figure 1, the boundary of this region is drawn assuming that $2r < \tilde{\pi}$. If $2r < \tilde{\pi}$,this point would lie on the x axis between $\tilde{\pi} - r$ and $\tilde{\pi}$.

[6] In Figure 1, the boundary dividing these two subregions is illustrative. In the appendix, we show actual boundary is defined by the equality $\tilde{\pi}^2(\tilde{\pi} \ -b) - r(\tilde{\pi} \ + \pi - r)^2 = 0$.

In region III of the parameter space, the equilibrium expected value of rents earned by the incumbent and the entrant are

$$V^i = \tilde{\pi} - r + rLn\left(\frac{r}{\tilde{\pi}}\left(\frac{\tilde{\pi} + \pi - b}{\tilde{\pi} - b}\right)\right) \text{ and}$$

$$V^e = r\left(\frac{\pi - b}{r}\right) + rLn\left(\frac{\tilde{\pi}}{\tilde{\pi} + \pi - b}\right),$$

respectively.

The model is as simple as can be and yet yields a rich set of comparative static results in terms of the R&D expenditures and ex ante market values of the incumbent and a prospective entrant. For our purposes, the question is how the behavior of incumbent and entrant firms changes as we reduce the cost of marketing capital (in our figure, fix $\tilde{\pi}, \pi$, and r and then observe the change in regions as we reduce b). We might start with an R&D intensive industry dominated by an incumbent and eventually observe entry, initially by firms that are not as R&D intensive as the incumbent (a movement from region II to III). Alternatively, we might begin with an industry that is not R&D intensive and eventually observe entry by R&D intensive firms, and if b falls enough, the incumbent might also start doing R&D (a movement from region I to IV and finally into III). In the latter case, we might observe equilibria where either the incumbent or the entrant does more R&D than its rival.

2.2. *Identifying the Effects of Changes in Marketing Capital*

In our empirical analysis of actual firm behavior, we examine the effects of changes in various parameters on the R&D intensity and the market value of incumbent and non-incumbent firms. We also estimate R&D reaction functions of these firms and examine the change in their slopes and intercepts over time. We argue this is sufficient to identify the predominant effect of changes in barriers to entry on firm behavior. This identification strategy follows from the comparative static results of the model, which are described in Table 1.[7] Notice, for example, that declines in the cost of marketing capital and the relative price of R&D are associated with similar (but not identical) changes in the R&D and reaction functions of incumbent and entrant firms, but very different implications in terms of changes in firm value.

2.2.1. *Accounting for entry by more than one firm*

A pure duopoly model may not be sufficient to characterize all the effects of falling barriers to entry over time. In the appendix, we present results of the model generalized to allow for the possibility of entry by more than one firm. We do this by adding a second fixed cost (c) that entrants must sink

[7] We omit the derivation of these results as they follow directly from the closed forms in Figure 1, and the reaction functions (above).

prior to engaging in R&D. For an appropriately chosen value of c, there exists a non-empty region of the parameter space where two firms will enter. This region is defined by a participation constraint whose boundary lies everywhere below the upper boundary of Region III in Figure 1. Thus in the richer model, the incumbent encounters a competitive fringe.

Consider two economies that differ only in the magnitude of the fixed cost of R&D. In the second economy, c is such that two firms are just indifferent about entering. In the first economy the fixed cost of R&D is $c + \varepsilon$. In the appendix, we show that all firms do less R&D in the second economy than in the first, and yet the probability of at least one successful innovation is higher in the second. And while the two entrants each do less R&D than the single entrant in the first economy, the sum of their R&D is higher. The ex ante value of the incumbent is higher in the second economy. The ex ante value of the entrant in the first economy is larger than in the second, where it is zero.

For changes in the exogenous parameters that do not induce additional entry, the results reported in Table 1 remain valid for the case of two active entrants. For example, as b falls, all firms will do more R&D, the value of the incumbent falls and the value of entrant(s) rises. If instead we consider reductions in c, the value of entrant firms rises, but there is no effect on the value of the incumbent unless an additional firm enters. In that case, the value of the entrants again falls to zero. And unless additional entry occurs, there is no change in the R&D performed by any firm. Thus we can use changes in R&D to distinguish between declines in the cost of marketing capital and declines in the fixed cost of R&D.

3. Data

We test our theory by using annual Compustat data from 1950 to 1999. Compustat compiles its data primarily from corporate annual reports and SEC filings. The data differ from NSF data along two dimensions. One is the nature of the universe: the NSF and Compustat may observe the same R&D at a different ownership level; typically, we believe that the NSF may be obtaining information from a subsidiary company whereas Compustat records data from a parent. The other is completeness–Compustat is a data set of security-issuing firms, while the NSF aims at measuring the R&D universe through a suitable random sampling frame.

We define R&D as reported R&D expense, Compustat no. 46. We identify firm size by numbers of employees, Compustat no. 29. To measure R&D intensity we use data on sales (net), Compustat no. 12, and on operating expense, which we define as cost of goods sold (Compustat no. 41) plus selling, general, and administrative expenses (Compustat no. 189). Operating expense is a better measure of nominal firm scale than sales for those new firms that do not have substantial sales. Typically R&D is expensed rather than capitalized and is thus included in operating expense, in which case the ratio of R&D to operating expense will be less than or equal to one, reducing the need to censor observations.

Because we wish to focus on strategic interactions between firms (see below), we define industries narrowly. We count four-digit SIC codes as separate industries whenever there are at least five firms with 30 or more years of financial data over the years 1950-99. For industries that do not meet this criterion, we aggregate to the three-digit SIC level, excluding those firms in the four-digit industries that meet our criterion. This results in 196 separate industries. We calculated an overall R&D intensity for these industries, dividing the sum of R&D expenditures by the sum of sales and identify 69 with a ratio of R&D to sales of 1 percent or higher in 1973. We call these R&D industries.[8]

We want to identify long-lived, large industrial corporations as our incumbent firms. We choose firms with more than 25 thousand employees in 1965 and focus on the set of incumbent firms in R&D intensive industries (defined above).[9] We identify 68 of these firms spread across 28 R&D industries (Table 2).[10] Together, these firms in 1974 accounted for 55 percent of the R&D performed by all private corporations reported in Compustat and for 77 percent of the R&D in their industries in that year (Table 3). Within their industries, these firms represented just 5 percent of all firms, but 73 percent of the operating expenditures.

We call these firms incumbents, because not only are they large firms but most of them had been large for an extended period of time. 44 of the 68 are listed in Chandler's list of the 200 largest U.S. industrial firms for the year 1948; and 34 were on Chandler's top 200 list for 1930. Moreover, as late as 1983, 58 of the 68 still had at least 25 thousand employees. Thus the majority of these firms were among the top industrial firms in the U.S. for half a century, and nearly all were very large for two decades. These large industrial firms are primarily makers of durable goods such as transportation equipment (including aerospace, cars, and tires), business equipment (electrical, construction, farm, and office), and glass. The list also includes chemical producers, including pharmaceuticals, and a few producers of consumer goods.

Table 3 shows two basic trends. First, the R&D-intensive industries increased their share of R&D, as measured in Compustat. Second, the incumbent R&D industries maintained their share through 1989 but, thereafter, the share of R&D in non-incumbent industries rose sharply. Using our definition, 69 R&D intensive industries accounted for a little more than 80 percent of total private R&D expenditures through the late 1980s and a higher share thereafter. Similarly, until about 1990 the share of R&D spending concentrated in the 28 R&D-intensive industries with an incumbent firm was about

[8] Details of our data set construction are found in a separate appendix available from the authors.

[9] We have omitted GTE, a telephone company operator that had a subsidiary with R&D, Sylvania; telephone companies were heavily regulated throughout most of this period, with most of the R&D performed by the jointly held Bell Labs.

[10] There are an additional 73 incumbents in non-R&D-intensive industries.

70 percent; thereafter it declined.[11]

The share of all private R&D accounted for by incumbent firms in R&D industries has fallen over time, from 55 percent in 1974 to about 35 percent in 1999, with most of this decline occurring during the 1990s. In 1974, the share of R&D spent in these industries attributable to non-incumbent firms was only 23 percent; in 1999 they accounted for 45 percent. Thus while R&D remains concentrated within a narrow set of industries, a rising share of this R&D is being performed by younger, smaller firms. And, as Figure 2 shows, this is not simply an artifact of the loss of incumbents over time; rather it is the increasing economic importance of R&D among smaller firms.

Table 4 documents the distinct rise in R&D intensity of U.S. firms over time, particularly in those industries that were already R&D intensive in 1973. And while the R&D intensity of incumbent firms has grown, the increase has been even higher among the non-incumbent firms. In 1974, the R&D intensity of the incumbents was 23 percent higher than for other firms in the same industries. By 1999, the R&D intensity of incumbent firms was 40 percent lower.

4. Empirical Results

We analyze how research and development expenditures and firm market value were influenced by changes in the cost of marketing capital. We proxy this cost by its dual, the rate of investment in computer hardware, using the U.S. aggregate business fixed investment in computers and peripheral equipment in nominal terms as a percentage of total U.S. gross domestic product, which we call computer share, or *comp* for short.[12] We restrict our regressions to the period from 1973 to 1997; the earlier date is the date from which we have reasonably complete data on R&D, and the latter date is chosen to exclude the worst effects of the Internet bubble in 1998 and after.

4.1. R&D Regressions

First, we examine the reaction of firms' research and development and market value to rivals' R&D lagged and market value lagged. All our regression data are scaled by operating expense, defined above. Rivals' R&D lagged and market value lagged are defined as follows:

$$(R\&D/OpExp)_{jt-1}^{\tilde{}i} \equiv \frac{\sum_{k\neq i} R\&D_{kjt-1}}{\sum_{k\neq i} OpExp_{kjt-1}}$$

[11] This decline is not simply due to exit by incumbent firms. We classify industries as incumbent industries if they ever included an incumbent firm.

[12] We are constructing industry specific measures of computer investment and technological opportunity (patenting) and will report results using these measures in a later version of the paper.

where i and k are firm subscripts, j is a three or four digit industry group, and t is time. Similarly,

$$(MV/OpExp)_{jt-1}^{\tilde{}i} \equiv \frac{\sum_{k \neq i} MV_{kjt-1}}{\sum_{k \neq i} OpExp_{kjt-1}}$$

where MV is market value, equal to shares outstanding at the end of the year times end-of-year price.

According to our model, as the cost of marketing capital falls, R&D should become more competitive, as entrants perceive incumbents' markets as more vulnerable. As such, we expect all firms, and particularly our long-term incumbents, to increase their R&D in response to R&D by their rivals.

We run simple reaction function regressions that have on the left-hand side own R&D expenditures (scaled by own operating expenditures) and, on the right-hand side, the comparable R&D intensity of the firm's rivals, i.e., that of the other firms in the same industry (defined above).

$$\frac{R\&D_{it}}{OpExp_{it}} = \alpha_0 + \alpha_1 * \left(\frac{R\&D}{OpExp}\right)_{t-1}^{\tilde{}i} + \alpha_2 * comp_{t-1} * \left(\frac{R\&D}{OpExp}\right)_{t-1}^{\tilde{}i} + u_i + v_t + \epsilon_{it}$$

We perform this regression on the set of R&D-intensive industries as a whole and four main subsets. All the regressions reported in the paper use a one-year lag of rivals' R&D intensity, but similar results are obtained using contemporaneous values. We then interact rivals' R&D intensity with computer share, measured in percentage points of GDP. This ratio has risen over time (Figure 4). What we expect to see is that as computerization rises, firms compete in R&D markets more aggressively, by increasing their R&D in response to others in the same industry increasing their R&D.

Our regressions are fixed effect regressions with year dummies. We have 4,029 firms in all, averaging just over eight annual observations per firm. Taking all firms together, we see in Table 6 that the coefficient on the term $comp_{t-1} * (R\&D/OpExp)_{t-1}^{\tilde{}i}$ is 0.3964, a coefficient that is both economically and statistically significant. The *comp* variable rises from 0.2 to 1.0 over the period 1973 to 1997, so the net effect of rivals' R&D goes from -0.1 to 0.2; in the earliest period firms react mildly negatively to R&D in the same industry, while over time this reaction becomes positive. Since rivals' R&D has roughly half the variation of own R&D, the coefficient of 0.2 suggests that about one-tenth of "within" movements in R&D can be accounted for by this reaction by the end of the period.

One concern in this analysis is that the rise in computer share necessarily has a more complex interpretation for the computer industries, which we define as including electronic computers (SIC 357), electronic components (SIC 367) and computer software (SIC 737). The development of the microprocessor influenced and was influenced by R&D in these industries. We therefore separate these industries from the non-computer industries. Perhaps surprisingly, computer share has a slightly weaker impact on the computer industries than on the others. It is worth considering that the dominant firm in these industries was IBM, which initially was the main developer and beneficiary of the personal computer. For the non-computer industries, we divide the total into two types: the industries that include long-term incumbents, which we call incumbent industries, and industries without incumbent firms. Within the incumbent industries, we allow different responses between the long-term incumbents themselves and the other firms in the industries.

We expect to find a somewhat different interaction between the long-term incumbents and their rivals than in the industries without incumbent firms. What we find is that there is a higher degree of strategic interaction in the industries with incumbent firms, and this strategic interaction arose as computerization increased. For long-term incumbents, the coefficient on rivals' R&D is 0.83, a stronger reaction than for other firms in the same industries. Since rivals' R&D has a "within" standard deviation that is two-thirds the size of that for own R&D, the impact of rivals' R&D accounts for more than 60 percent own R&D by the end of the period. This substantial economic impact is reflected in the large proportion of R&D accounted for by the regression (the "within" R^2 is 0.39). While firms other than the long-term incumbents have a smaller coefficient on the interaction of computer share and rivals' R&D (lagged), it is still larger than for firms in other industries.

In non-computer, non-incumbent industries, research and development expenditures are overall negatively related to rivals' R&D lagged, and as computerization increased, this relationship remained negative but became attenuated over time.

4.1.1. Adding market value to the R&D regressions

The temporal relationships that define the basic reaction function regressions do not include any forward looking variables that might capture R&D investment opportunities. We therefore add lagged market value, both own and rivals', to the regression.

$$\begin{aligned}\frac{R\&D_{it}}{OpExp_{it}} &= \alpha_0 + \alpha_1 * \left(\frac{R\&D}{OpExp}\right)^{\tilde{}i}_{t-1} + \alpha_2 * comp_{t-1} * \left(\frac{R\&D}{OpExp}\right)^{\tilde{}i}_{t-1} \\ &+ \alpha_3 * \left(\frac{MV}{OpExp}\right)^{i}_{t} + \alpha_4 * comp_t * \left(\frac{MV}{OpExp}\right)^{i}_{t} + \alpha_5 * \left(\frac{MV}{OpExp}\right)^{\tilde{}i}_{t-1} \\ &+ \alpha_6 * comp_{t-1} * \left(\frac{MV}{OpExp}\right)^{\tilde{}i}_{t-1} + u_i + v_t + \epsilon_{it}\end{aligned}$$

When we do so the coefficients on the interaction of computer share and rivals' lagged R&D intensity tend to diminish, as do the differences in these coefficients across the different categories of firms (Table 7). The one exception is among firms in the non-computer, non-incumbent industries, where the coefficient rises slightly. With the exception of firms in the computer industries, the coefficients remain statistically significant

As expected, increases in own lagged market value, when interacted with computer share, is positively related to R&D. The coefficients are statistically and economically significant (with the exception of other firms in R&D industries with incumbent firms). There is only one group of firms whose R&D intensity also appears to respond to increases in their rivals' market value interacted with computer share–other firms in incumbent industries. Note that the R&D intensity of incumbent firms also responds to their own lagged market value. So it appears that R&D in incumbent industries is strongly positively influenced by market value increases for incumbent firms. This might tend to soften our earlier suggestion that incumbent firms were reacting purely to other firms' R&D. Alternatively, one might argue that when an incumbent firm's rivals increase their R&D, this suggests better R&D investment opportunities for the incumbent, whose market value rises in anticipation of its rising R&D.

A curious exception to the general pattern is that for non-computer non-incumbent industries, as computerization increased their reaction to rivals' market value increases was to reduce their R&D. We do not yet understand why this strong reaction occurs.

However we interpret these market value interaction terms, it appears evident that as computerization increased, all industries experienced more strategic interaction in R&D expenditures.

4.2. Market Value Regressions

According to our basic model, the increased competitiveness of R&D markets should lower the market value of R&D performing incumbents but raise the market value of R&D performing entrants. However, the latter result may not hold when more than one firm is able to enter. In that case, there are discontinuities in the effects of changes in marketing capital on the value of firms and these discontinuities are larger for the entrants. Moreover, once firms successfully enter, they become incumbents (albeit perhaps in small markets). And because there is more competition, the market value they gain from R&D is likely to be lower than before marketing capital fell in price.

4.2.1. Simple market value regressions

We begin with fixed effects regressions with year dummies in which we have market value (at the end of the year) on the left-hand side and R&D on the right-hand side. To see the effect of the fall in price of marketing capital, we interact computer share with R&D, and we also include book value of assets to control for the value of tangible assets (including net financial assets).

$$\frac{MV_{it}}{OpExp_{it}} = \beta_0 + \beta_1 * \frac{BV_{it}}{OpExp_{it}} + \beta_2 * \frac{R\&D_{it}}{OpExp_{it}} + \beta_3 * comp_t * \frac{R\&D_{it}}{OpExp_{it}} + u_i + v_t + \epsilon_{it}$$

For all firms, we get the results we expect (Table 9). Initially, own R&D expenditures are valued at a high multiple, close to 5. R&D by incumbent firms earns monopoly rents, on average. However, over time as the cost of marketing capital falls, R&D falls in value. This appears to be the crash in value of research and development discussed by Hall (1993).[13] This suggests that the value of new R&D was eroded by the rise of computerization, primarily in the computer and electronic industries but also among firms in other non-incumbent R&D industries.

We expected to find a comparable decline in the value of R&D for long-term incumbent firms, but the coefficient is positive and insignificant. For many incumbents, it appears their R&D remained a source of monopoly profits, despite increased entry, and that their R&D efforts were often successful. Thus the crash in value of R&D does not appear to have happened to long-term incumbents, at least taken as a group.

The coefficient on book value in all cases is significantly greater than unity. One interpretation of this coefficient is that it is a measure of marginal q, reflecting the rise in market value with additional tangible investments. This interpretation suggests market power and, in turn may reflect the success of R&D which itself confers market power.

4.2.2. Adding rival R&D to the market value regressions

In our final set of regressions, we add rival R&D, lagged one year and, in addition, interact it with computer share (Table 10). This allows us to test separately for the effects of increased R&D competition. In addition, we also allow for the possibility that the market value of the firm's other assets has eroded over time.

$$\begin{aligned}\frac{MV_{it}}{OpExp_{it}} &= \beta_0 + \beta_1 * \frac{BV_{it}}{OpExp_{it}} + \beta_2 * \frac{R\&D_{it}}{OpExp_{it}} + \beta_3 * comp_t * \frac{R\&D_{it}}{OpExp_{it}} \\ &\quad + \beta_4 * comp_t * \frac{BV_{it}}{OpExp_{it}} + \beta_5 * \left(\frac{R\&D}{OpExp}\right)^{\tilde{}i}_{t-1} \\ &\quad + \beta_6 * comp_{t-1} * \left(\frac{R\&D}{OpExp}\right)^{\tilde{}i}_{t-1} + u_i + v_t + \epsilon_{it}\end{aligned}$$

The book value of firm assets declines with computerization among firms in the computing industries and firms in the non-incumbent R&D industries. On net, however, book values remain above 1. The R&D crash – a fall in

[13] Hall and Kim (2000) report some evidence of a modest recovery in the market value of R&D among U.S. firms in the 1990s.

the value of own R&D identified in the previous regression– is by and large replaced by the impact of rivals' R&D. Compared to the coefficients reported in Table 9, the initial value of own R&D shrinks, as does the interaction with computer share, which typically becomes insignificant. The exception is in the incumbent industries, where the value of own R&D rises with computerization for incumbent firms but falls among the other firms in those industries.

Overall, we see that rivals' R&D eroded firm market value as computerization increased. This effect is relative to an earlier period in which rivals' R&D had a consistently positive effect on own market value. The erosion of market value over time comes to outweigh the initial positive effect in computer industries and in industries without incumbent firms. Thus it appears that the crash in the value of R&D may in large part be attributable to the impact of more competition in R&D markets. However, this impact is again not as strong in the incumbent industries. Incumbent firms in particular appear to have retained substantial market power, although they have had to perform more R&D in order to do so. And while the interaction of book value with computer share is negative, it is not large enough to drive book value to unity.

5. Conclusion

We have hypothesized that the rise of computerization made market entry into R&D-intensive industries easier. We argue that computerization reduced the cost of marketing capital. Under our model, computerization should increase R&D activity by both entrant and incumbent and should lower the market value of R&D by incumbents. The evidence we have presented shows clearly that as computerization increased R&D by all firms increased.

Overall, as computerization increased, the market value of firms fell, but this appears to have been primarily due to R&D by rivals, rather than a direct decline in the value of R&D. And surprisingly, the large long-term incumbents – while they had to respond vigorously to R&D by rivals – were able to retain a large part of their market value, unlike smaller incumbents.

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6. Appendix

6.1. Allowing for Additional Entry

We modify the objective functions in the text to include a fixed cost (c) that entrants must sink if they are to engage in R&D. There is one complication: in the instance where both entrants successfully innovate, and the entrant does not, there is no pure strategy equilibrium. Instead, the entrants randomize over their decision to sink b. In the symmetric case, the probability of sinking b, denoted α, is determined by the expression

$$\alpha(1-\alpha)\left[\tilde{\pi}-b\right]-\alpha^2 b=0.$$

The resulting firm value functions are then

$$V_2^j=\theta_2^j(1-\theta_2^i)(1-\theta_2^k)[\tilde{\pi}\ -b]+rLn(1-\theta_2^j)-c$$

and

$$V_2^i=\theta_2^i\tilde{\pi}+(1-\theta_2^i)\left\{(1-\theta_2^j)(1-\theta_2^k)+\theta_2^j\theta_2^k(1-\alpha)^2\right\}\pi+rLn(1-\theta_2^i),$$

where j and k denote the entrant firms and we use a subscript to distinguish this problem from the case with a single entrant. The associated first order conditions, for the symmetric case, are

$$\begin{aligned}\tilde{\pi}\ -\left\{(1-\theta_2^e)^2+\theta_2^{e2}(1-\alpha)^2\right\}\pi-\frac{r}{(1-\theta_2^i)} &= 0 \text{ and}\\ (1-\theta_2^e)^2-\frac{r}{(1-\theta_2^i)\left[\tilde{\pi}-b\right]} &= 0.\end{aligned}$$

The slope of reaction functions have the same sign as in the duopoly case. The derivatives of the reaction functions with respect to $\tilde{\pi}, \pi, r,$ and b take the same sign as in the duopoly case.

The closed form solution for the entrants' R&D decision is then

$$\theta_2^e=\frac{\tilde{\pi}+\pi-b-\sqrt{\tilde{\pi}^2+[\pi-b]\left[\tilde{\pi}-\pi(1-\alpha)^2\right]}}{\tilde{\pi}+\pi-b+\pi(1-\alpha)^2}.$$

Lemma 1 $\theta_2^e \leq \theta_1^e$ *but* $(1-\theta_2^e)^2 \leq (1-\theta_1^e)$.

Proof. The first part of the lemma follows from the fact that

$$(1-\theta_2^e) \leq (1-\theta_1^e) = \tilde{\pi}+\pi-b-\sqrt{[\tilde{\pi}+\pi-b]^2-[\pi-b]\left[\tilde{\pi}+\pi-b+\pi(1-\alpha)^2\right]}.$$

The first order conditions imply $\tilde{\pi} \ -\theta_2^{e2}(1-\alpha)^2\pi-(1-\theta_2^e)^2\left[\tilde{\pi}+\pi-b\right]=0$. From this we know

$$(1-\theta_2^e)^2 = \frac{\tilde{\pi} \ -\theta_2^{e2}(1-\alpha)^2\pi}{\tilde{\pi}+\pi-b} \leq \frac{\tilde{\pi}}{\tilde{\pi}+\pi-b} = (1-\theta_1^e).$$

■

Lemma 2 $\theta_2^i \leq \theta_1^i$.

Proof. From the first order condition for the incumbent,

$$(1-\theta_2^i) = \frac{r\left[\tilde{\pi}+\pi-b\right]}{\tilde{\pi}\left[\tilde{\pi}-b\right]}+\frac{r\pi(1-\alpha)^2}{\tilde{\pi}\left[\tilde{\pi}-b\right]}\left(\frac{\theta_2^e}{1-\theta_2^e}\right)^2 = (1-\theta_1^i)+\frac{r\pi(1-\alpha)^2}{\tilde{\pi}\left[\tilde{\pi}-b\right]}\left(\frac{\theta_2^e}{1-\theta_2^e}\right)^2.$$

■

Lemma 3 $V_1^j > V_2^j$ *and* $V_2^i > V_1^i$.

Problem 4 ***Proof.*** *After making substitutions using the first order conditions, the value function for the incumbent and entrants can be expressed as*

$$\begin{aligned}
\frac{V_1^i}{r} &= \tilde{\pi}-r+Ln\left(1-\theta_1^i\right); \\
\frac{V_2^i}{r} &= \tilde{\pi}-r+Ln\left(1-\theta_2^i\right); \\
\frac{V_1^e}{r} &= \frac{\theta_1^e}{1-\theta_1^e}+Ln\left(1-\theta_1^e\right)-\frac{c}{r}; \quad \textit{and} \\
\frac{V_2^e}{r} &= \frac{\theta_2^e}{1-\theta_2^e}+Ln\left(1-\theta_2^e\right)-\frac{c}{r}.
\end{aligned}$$

The result follows from the previous lemmas.

Corollary 5 *The comparative static results for firm market values with two entrants take the same sign as in the duopoly case if the sign of the derivatives of* θ_2^i *and* θ_2^e *with respect to* $\tilde{\pi}, \pi, r,$ *and* b *take the same sign as the derivatives of* θ_1^i *and* θ_1^e.

■

For the symmetric case, the participation constraint for two entrants is defined by

$$\Psi \equiv V_2^e = \frac{r\theta_2^e}{1-\theta_2^e} + rLn\left(1-\theta_2^e\right) - c = 0.$$

Next we characterize this constraint in the (b, π) space we use in Figure 1. Let $\hat{b}(\tilde{\pi}, \pi, r, c)$ denote the cost of marketing capital where this participation constraint just binds. The slope of the participation constraint is then $-\frac{\partial\Psi/\partial b}{\partial\Psi/\partial\pi}$, where

$$\frac{\partial\Psi}{\partial\pi} = \frac{\theta_2^e}{\left(1-\theta_2^e\right)^2} \cdot \frac{\left(1-\theta_2^e\right)^2 + \theta_2^{e2}(1-\alpha)^2}{2\sqrt{\tilde{\pi}^2 + [\pi - b]\left[\tilde{\pi} - \pi(1-\alpha)^2\right]}} = \frac{\theta_2^e}{\left(1-\theta_2^e\right)^2} \cdot \frac{\partial\theta_2^e}{\partial\pi} > 0$$

and

$$\frac{\partial\Psi}{\partial b} = \frac{\theta_2^e}{\left(1-\theta_2^e\right)^2} \cdot \frac{2\theta_2^{e2}(1-\alpha)^2\frac{\pi}{\tilde{\pi}} - \left(1-\theta_2^e\right)^2}{2\sqrt{\tilde{\pi}^2 + [\pi - b]\left[\tilde{\pi} - \pi(1-\alpha)^2\right]}} = \frac{\theta_2^e}{\left(1-\theta_2^e\right)^2} \cdot \frac{\partial\theta_2^e}{\partial b}.$$

At $\pi = 0$, $\frac{\partial\hat{b}}{\partial\pi} = 1$. As π increases, the slope falls:

$$\frac{\partial^2\hat{b}}{\partial^2\pi} = \frac{2\left\{\left(1-\theta_2^e\right)\left[\frac{\partial\hat{b}}{\partial\pi} - 1\right]\frac{\partial\theta_2^e}{\partial\pi} - (1-\alpha)\theta_2^e\left[\frac{2\pi}{\tilde{\pi}} + (1-\alpha)\right]\frac{\partial\theta_2^e}{\partial\pi} - 2(1-\alpha)\frac{\theta_2^{e2}}{\tilde{\pi}}\right\}}{\left(1-\theta_2^e\right)^2 + \theta_2^{e2}(1-\alpha)^2} < 0.$$

Lemma 6 $\frac{\partial\theta_2^e}{\partial b} \leq 0.$

Proof. The sign of this derivative is the sign of the following expression:

$$\frac{b\pi}{\tilde{\pi}^2}\left(\frac{\theta_2^e}{1-\theta_2^e}\right)^2 - \frac{1}{2}.$$

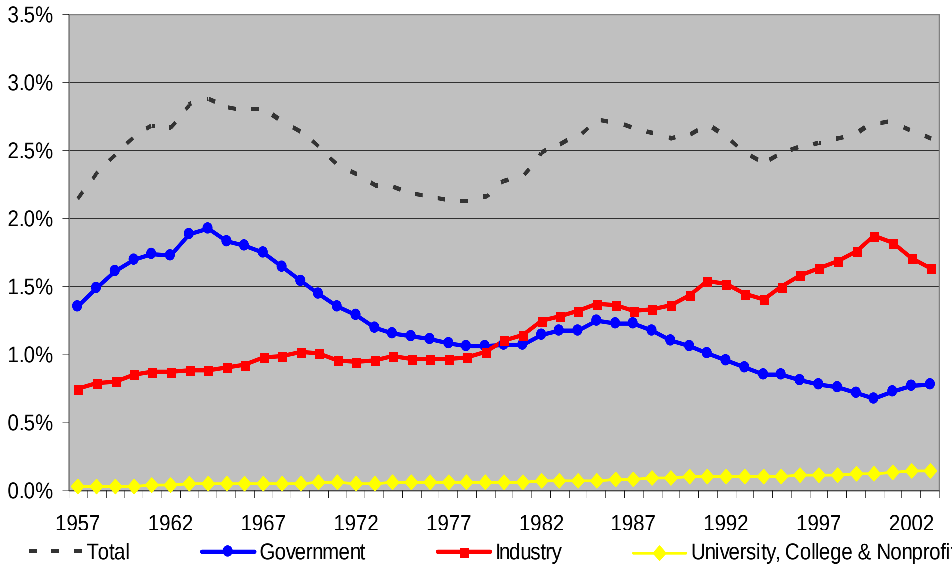
Since $\frac{\partial\theta_2^e}{\partial\pi} > 0$, the odds of the entrant's success are maximized at $\pi = \tilde{\pi}$. For this value of π, the expression becomes

$$(1-\alpha)\left(\frac{1+\alpha-\sqrt{1+\alpha^2(2-\alpha)}}{(1-\alpha)^2+\sqrt{1+\alpha^2(2-\alpha)}}\right)^2.$$

We maximize this expression numerically in Mathematica, subject to the constraint $1 \geq \alpha \geq 0$. The maximum value is -0.48 where $\alpha = 0.62$. ■

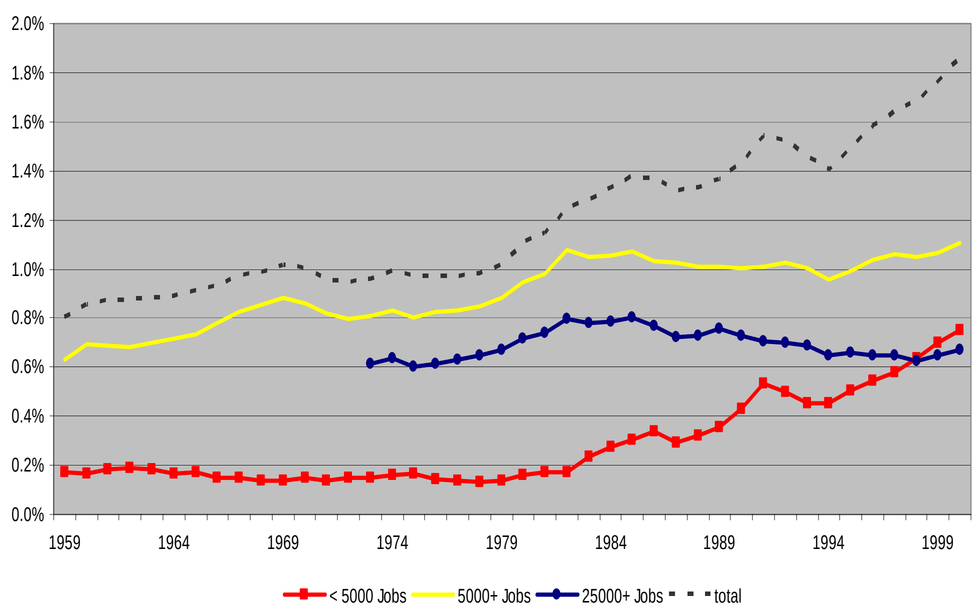
The Democratization of U.S. R&D After 1980

Figure 1: R&D by Source of Funds, 1957-2003
(percent of GDP)



Source: National Science Foundation and authors' calculations

Figure 2: R&D by firm size
(percent of GDP)



Source: National Science Foundation and authors' calculations

Figure 3: State Space Diagram - Duopoly Case

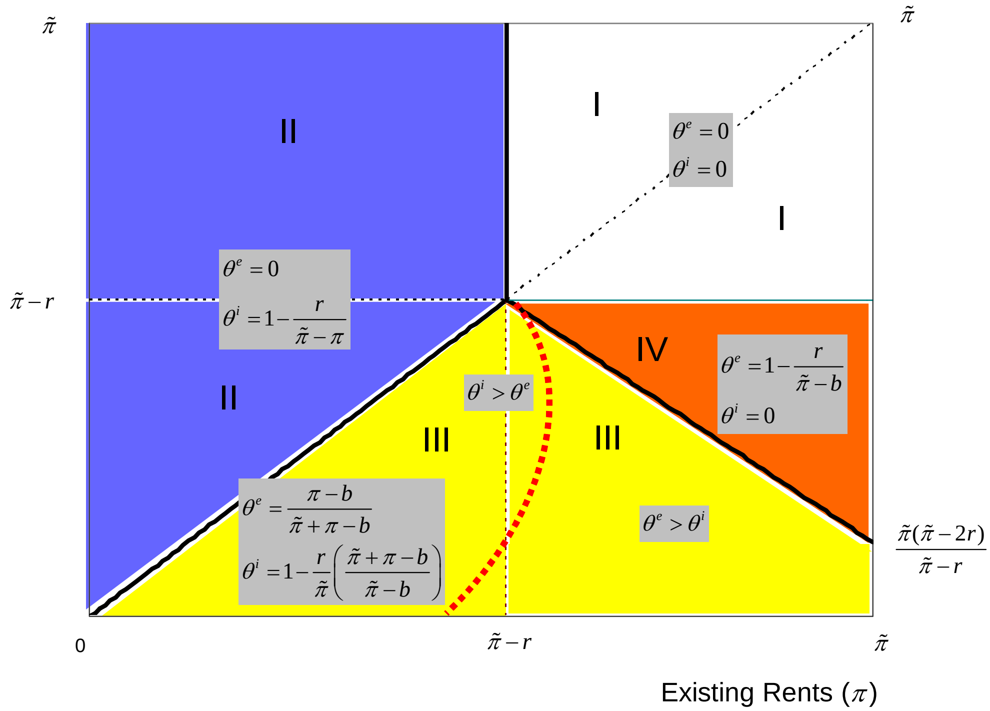
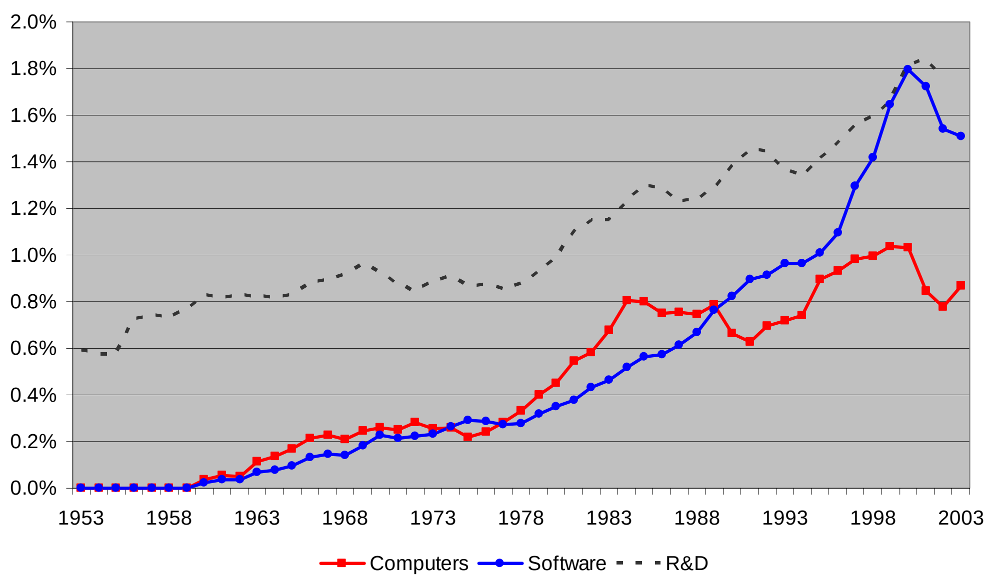


Figure 4: Investment in R&D, Computers, & Software
(Percent of GDP)



Source: Bureau of Economic Analysis, National Science Foundation, and authors' calculations.

Table 1: Testable Implications of the Model[†]				
	Change in Exogenous Parameter			
	↓ Marketing Capital (b)	↓ R&D Cost (r)	↑ Invention Size ($\tilde{\pi}$)	↑ Existing Rents (π)
R&D				
Incumbent	↑	↑	↑	↓
Entrant	↑	∅	↓	↑
Slope of R&D Reaction Function				
Incumbent	∅	↑	↑	↓
Entrant	↑	↑	↑	∅
Ex Ante Firm Value				
Incumbent	↓	↑	↑	↑
Entrant	↑	↓	↑	↑

[†]: For results for the case of entry by more than one firm, see section 2.2.1 and the Appendix.

Table 2: Incumbent Firms in R&D Industries

Company	Jobs, 1965	Company	Jobs, 1965
Alcoa Inc	48,200	Honeywell Inc	54,600
American Cyanamid Co	34,100	Honeywell International Inc	36,600
American Home Products Corp	30,600	Intl Business Machines Corp	172,445
American Motors Corp	31,900	ITT Industries Inc	199,000
American Standard Cos Inc	37,200	Litton Industries Inc	65,600
Babcock & Wilcox Co	25,000	Lockheed Martin Corp	81,300
Bendix Corp	46,500	Martin Marietta Corp	30,000
Bicoastal Corp	101,830	McDonnell Douglas Corp	36,300
Boeing Co	93,400	Motorola Inc	30,000
Borg Warner Inc	35,850	Navistar International	111,980
Caterpillar Inc	50,800	NCR Corp	73,000
CBS Corp	115,100	Olin Corp	43,000
Celanese Corp	42,200	Otis Elevator Co	37,900
Chrysler Corp	166,800	Owens-Illinois Inc	49,000
Clevite Corp	29,141	Pfizer Inc	30,000
Colgate-Palmolive Co	26,200	Pharmacia Corp	56,200
Deere & Co	41,600	PPG Industries Inc	38,100
Douglas Aircraft Inc	60,300	Procter & Gamble Co	35,300
Dow Chemical	33,800	R R Realizations Ltd	49,700
Du Pont (E I) De Nemours	115,400	Raytheon Co	32,600
Eastman Kodak Co	55,500	RCA Corp	100,000
Eaton Corp	36,000	Revlon Group Inc	31,600
EMI Ltd	28,600	Reynolds Metals Co	30,300
Firestone Tire & Rubber Co	88,400	Rockwell Intl Corp	99,900
FMC Corp	37,600	Sperry Corp	93,600
Ford Motor Co	364,500	Texas Instruments Inc	34,500
Gencorp Inc	45,000	Textron Inc	41,000
General Dynamics Corp	84,600	TRW Inc	46,900
General Electric Co	257,900	Union Carbide Corp	73,900
General Motors Corp	735,000	Uniroyal Inc	65,000
Goodrich (B F) Co	43,900	Unisys Corp	35,200
Goodyear Tire & Rubber Co	103,700	United Technologies Corp	71,800
Grace (W R) & Co	53,400	Varity Corp	45,700
Grumman Corp	30,000	Viad Corp	32,400

Notes: Incumbent firms are those firms with at least 25,000 employees in 1965. R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973.

Table 3: Distribution of R&D (Percent of Total)					
		R&D Industries			
		Incumbent Industries			Non-Incumbent Industries
Year	Non-R&D Industries	All Firms	Incumbent Firms	Other Firms	
1974	16.8	71.2	54.6	16.7	12.0
1979	17.3	70.8	53.2	17.5	11.9
1984	18.3	68.3	48.2	20.2	13.4
1989	15.7	71.0	49.1	21.9	13.3
1994	13.6	67.6	41.6	26.0	18.8
1999	7.6	63.5	34.7	28.8	28.9

Notes: Incumbent firms are those firms with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973.

Table 4: R&D Intensity (R&D ÷ Operating Expense, percent)					
		R&D Industries			
		Incumbent Industries			Non-Incumbent Industries
Year	Non-R&D Industries	All Firms	Incumbent Firms	Other Firms	
1974	0.31	3.32	3.50	2.84	2.63
1979	0.31	3.32	3.49	2.90	3.00
1984	0.45	4.53	4.52	4.56	4.85
1989	0.46	5.08	4.89	5.56	4.72
1994	0.42	5.42	4.94	6.43	5.54
1999	0.28	6.38	5.56	7.75	7.01

Notes: Incumbent firms are those firms with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973.

Table 5: Statistics for R&D Reaction Function Regressions (1973-97)

	All R&D Industries		Computer Industries	Non-computer Industries		
				Incumbent Industries		Non-Incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
	Mean	Within Standard Deviation				
$\left(\frac{R\&D}{OpExp}\right)_t^i$	.0561	.0285	.0379	.0146	.0232	.0257
$\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	.0575	.0132	.0150	.0108	.0105	.0137
$\left(\frac{MV}{OpExp}\right)_{t-1}^i$	1.447	1.197	1.354	.478	1.078	1.212
$\left(\frac{MV}{OpExp}\right)_{t-1}^{\sim i}$	1.355	.644	0.714	.454	.490	.699
$comp*\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	.0392	.0154	.0184	.0131	.0128	.0152
$comp*\left(\frac{MV}{OpExp}\right)_{t-1}^i$	1.036	.901	1.034	.379	.797	.909
$comp*\left(\frac{MV}{OpExp}\right)_{t-1}^{\sim i}$	.931	.550	.663	.368	.385	.575
firms	4,029	4,029	1,273	60	923	1,767
observations	33,793	33,793	8,900	1,320	9,192	14,381
R&D Expense (Pct., 1973)		100.0 %	14.8 %	57.0%	18.3 %	10.0 %

Notes: R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973. Computer industries include firms in SICs 357, 367, or 737. Incumbent firms are companies with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. Comp is nominal investment in computers & software ÷ GDP.

Table 6: Simple Reaction Function Regressions with Fixed and Year Effects
(R&D Industries, 1973-97)

Dependent Variable:	All Firms	Computers	Non-computer Industries			
			Incumbent Industries			Non-incumbent Industries
$\left(\frac{R\&D}{OpExp}\right)_t^i$			All Firms	Incumbent Firms	Other Firms	
constant	.0524 .0015 .0000	.0785 .0055 .0000	.0221 .0018 .0000	.0232 .0023 .0000	.0224 .0021 .0000	.0543 .0019 .0000
$\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	-.1868 .0333 .0000	-.0803 .0895 .3693	.0548 .0557 .3253	.0284 .0816 .7275	.0433 .0632 .4935	-.2857 .0483 .0000
$comp*\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	.3964 .0357 .0000	.3418 .0986 .0005	.5734 .0580 .0000	.8277 .0916 .0000	.5640 .0653 .0000	.3021 .0530 .0000
n	33,793	8,900	10,512	1,320	9,192	14,381
Within R^2	.0263	.0251	.1034	.3857	.0898	.0172

Notes: 1st row is the coefficient; 2nd is the standard error; 3rd is the *p* value. R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973. Computer industries include firms in SICs 357, 367, or 737. Incumbent firms are companies with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. Comp is nominal investment in computers & software ÷ GDP.

Table 7: Full Reaction Function Regressions with Fixed and Year Effects
(R&D Industries, 1973-97)

Dependent Variable:	All Firms	Computers	Non-computer Industries			
$\left(\frac{R\&D}{OpExp}\right)_t^i$			Incumbent Industries			Non-incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
constant	4.989 .1567 .0000	7.192 .5903 .0000	3.381 .2177 .0000	2.155 .2248 .0000	2.223 .2221 .0000	5.037 .2161 .0000
$\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	-.1593 .0390 .0000	-.0655 .1186 .5807	.0293 .0589 .6197	.1086 .0910 .2330	.0282 .0769 .7142	-.2703 .0534 .0000
$comp*\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	.3687 .0465 .0000	.2366 .1498 .1142	.3524 .0693 .0000	.4607 .1108 .0000	.4372 .0939 .0000	.3817 .0625 .0000
$\left(\frac{MV}{OpExp}\right)_{t-1}^{i}$	-.0466 .0452 .3022	-.1121 .1227 .3610	-.0050 .0638 .9371	-.2510 .1540 .1033	.0998 .0363 .0060	.0113 .0613 .8535
$comp*\left(\frac{MV}{OpExp}\right)_{t-1}^{i}$	.4390 .0609 .0000	.5198 .1617 .0013	.4574 .0873 .0000	1.741 .2392 .0000	.0609 .0519 .2406	.2562 .0826 .0019
$\left(\frac{MV}{OpExp}\right)_{t-1}^{\sim i}$	-.0574 .0899 .5232	.0933 .2518 .7110	-.1435 .1218 .2389	-.0845 .2003 .6733	-.158 .134 .2367	.2239 .1457 .1245
$comp*\left(\frac{MV}{OpExp}\right)_{t-1}^{\sim i}$	-.0161 .1307 0.9017	.2435 .3614 .5004	.4369 .2011 .0299	.4031 .318 .2058	.6062 .2468 .0141	-.7517 .2068 .0003
n	33,793	8,900	10,512	1,320	9,192	14,381
Within R^2	.0392	.0352	.0894	.4557	.1166	.0298

Notes: 1st row is the coefficient; 2nd is the standard error; 3rd is the *p* value. Regression excludes observations with normalized market value (i.e., divided by operating expense) or the comparable measure for its rivals ≥ 14. R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973. Computer industries include firms in SICs 357, 367, or 737. Incumbent firms are companies with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. Comp is nominal investment in computers & software ÷ GDP.

Table 8: Statistics for Market Value Regressions (R&D Industries, 1973-97)						
				Non-computer industries		
				Incumbent Industries		
	All Firms	All Firms	Computers	Incumbent Firms	Other Firms	Non-incumbent Industries
	Mean	Within Standard Deviation				
$\left(\frac{MV}{OpExp}\right)_t^i$	1.433	1.139	1.294	.521	1.155	1.257
$\left(\frac{BV}{OpExp}\right)_t^i$	.5742	.2504	.2653	.1144	.2200	.2495
$\left(\frac{R\&D}{OpExp}\right)_t^i$	.0578	.0290	.0384	.0147	.0226	.0254
$\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	.0588	.0134	.0152	.0109	.0106	.0138
$comp*\left(\frac{BV}{OpExp}\right)_t^i$	.3930	.2088	.2173	.1178	.1909	.2112
$comp*\left(\frac{R\&D}{OpExp}\right)_t^i$	.0416	.0258	.0345	.0164	.0199	.0222
$comp*\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	.0403	.0157	.0187	.0131	.0129	.0152
firms	4,153	4,153	1,387	59	867	1,694
observations	34,508	34,508	9,455	1,304	8,638	13,584
Market Value (Pct., 1973)		100	19.2	40.4	27.8	12.6

Notes: Excludes observations with normalized market value (i.e., divided by operating expense) ≥ 14, normalized book value ≥ 4 or normalized book value ≤ -0.1. R R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973. Computer industries include firms in SICs 357, 367, or 737. Incumbent firms are companies with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. Comp is nominal investment in computers & software ÷ GDP.

Table 9: Simple Market Value Regressions with Fixed and Year Effects (R&D Industries, 1973-97)						
Dependent Variable:	All Firms	Computer Industries	Non-computer industries			
$\left(\frac{MV}{OpExp}\right)_t^i$			Incumbent Industries			Non-incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
constant	.2491 .0445 .0000	.5588 .1187 .0000	-.0172 .0577 .7653	-.1792 .0780 .0218	.0149 .0655 .8203	.4747 .0654 .0000
$\left(\frac{BV}{OpExp}\right)_t^i$	2.016 .0231 .0000	2.370 .0461 .0000	1.888 .0420 .0000	1.403 .1005 .0000	1.903 .0451 .0000	1.991 .0294 .0000
$\left(\frac{R\&D}{OpExp}\right)_t^i$	4.777 .5928 .0000	4.327 1.098 .0001	4.216 1.079 .0001	8.223 1.941 .0000	4.415 1.174 .0002	3.022 .7946 .0001
$comp*\left(\frac{R\&D}{OpExp}\right)_t^i$	-4.332 .7148 .0000	-4.581 1.309 .0005	-1.139 1.336 .3941	2.724 2.181 .2118	-1.826 1.460 .2111	-2.746 .9581 .0042
n	35,688	9,838	10,620	1,307	9,313	2,171
Within R^2	.2405	.3332	.2233	.4629	.2241	.2445

Notes: 1st row is the coefficient; 2nd is the standard error; 3rd is the *p* value. Market and book variables are year-end values. Regressions exclude observations with normalized market value (i.e., divided by operating expense) ≥ 14, normalized book value ≥ 4 or normalized book value ≤ -0.1. R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973. Computer industries include firms in SICs 357, 367, or 737. Incumbent firms are companies with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. Comp is nominal investment in computers & software ÷ GDP.

Table 10: Full Market Value Regressions with Fixed and Year effects
(R&D Industries, 1973-97)

Dependent Variable:	All Firms	Computer Industries	Non-computer industries			
$\left(\frac{MV}{OpExp}\right)_t^i$			Incumbent Industries			Non-incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
constant	-.0989 .0599 .0987	-.1411 .1690 .4038	-.3104 .0829 .0002	-.4214 .0956 .0000	-.2616 .0960 .0064	.2670 .0918 .0036
$\left(\frac{BV}{OpExp}\right)_t^i$	2.467 .0830 .0000	3.466 .0186 .0000	1.900 .1270 .0000	1.455 .2385 .0000	1.860 .1388 .0000	2.308 .1278 .0000
$comp*\left(\frac{BV}{OpExp}\right)_t^i$	-.6026 .1085 .0000	-1.423 .2412 .0000	-.0764 .1688 .6510	-.1620 .3171 .6096	-.0018 .1818 .9924	-.6821 .1670 .0000
$\left(\frac{R\&D}{OpExp}\right)_t^i$	1.701 .647 .0086	1.488 1.156 .1981	4.297 1.222 .0004	3.854 2.080 .0641	4.908 1.345 .0003	-.7616 1.057 .4712
$comp*\left(\frac{R\&D}{OpExp}\right)_t^i$	-.5665 .7929 .4749	-1.296 1.395 .3531	-1.646 1.531 .282	6.068 2.444 .0132	-2.934 1.692 .0829	1.8813 1.314 .1522
$\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	8.148 1.184 .0000	6.823 2.458 .0055	7.855 2.267 .0005	14.021 2.963 .0000	6.936 2.562 .0068	5.694 1.957 .0036
$comp*\left(\frac{R\&D}{OpExp}\right)_{t-1}^{\sim i}$	-10.333 1.316 .0000	-8.434 2.740 .0021	-1.641 2.158 .5045	-7.998 3.422 .0196	-.4810 2.755 .8614	-9.357 2.236 .0000
n	34,508	9,455	10,416	1,307	9,109	14,637
Within R^2	.2432	.3445	.2297	.4804	.2292	.2082

Notes: 1st row is the coefficient; 2nd is the standard error; 3rd is the *p* value. Market and book variables are year-end values. Regressions exclude observations with normalized market value (i.e., divided by operating expense) ≥ 14, normalized book value ≥ 4 or normalized book value ≤ -0.1. R&D industries are defined as industries where R&D/Sales ≥ 1 in 1973. Computer industries include firms in SICs 357, 367, or 737. Incumbent firms are companies with at least 25,000 employees in 1965. Incumbent industries are those SICs with at least one incumbent firm. Comp is nominal investment in computers & software ÷ GDP.