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

Robert M. Hunt
Leonard I. Nakamura

Research Department,
Federal Reserve Bank of Philadelphia[1]

First Draft: September 2004
This Draft: September 2010
Please do not circulate

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] Ten Independence Mall, Philadelphia, PA 19106.

We thank Annette Fratantaro for her excellent and tireless assistance. We also thank George Alessandria, James Bessen, Wesley Cohen, Vincenzo Denicolo, Bronwyn Hall, Christopher Laincz, Ulrich Kaiser, Baruch Lev, Elif Sen, Zhu Wang and seminar participants at Drexel University and the Kiel Workshop on Innovation, R&D, and Technology Adoption for helpful comments. The remaining errors are our own.

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 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 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

[2] Prior to this time, a power law – dubbed Grosch's law – held in computerization, which was that system power increased with the square of system cost (Mendelson 1987). Hence the most efficient systems required sufficient scale to amortize the required investment. Mendelson documents that these economies of scale disappeared in the 1980s.

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; 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 section we describe a model in which established firms initially have an advantage in investing in new product development because of their past investment in a customer base, which we call marketing capital. This model is related to the one found in 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. What is crucial about the characterization of this cost is (1) it is a fixed cost and (2) it is sunk *after* the firm knows the outcome of its R&D but before it can reach customers in the final market.

There are two firms. One firm–*the incumbent*–is earning positive rents on its earlier innovations. The other firm–the *entrant*–earns rents we can normalize to zero without loss of generality. 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.[3] 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 in this market. If both firms successfully innovate, and the entrant sinks its investment in marketing capital, the two firms will compete in prices. In equilibrium, the

[3] The results presented here are qualitatively the same if we allow for more firms (see the Appendix) or for non-drastic innovations.

entrant would never choose to do so, as it could not amortize the cost of R&D or its marketing capital.

The likelihood of success for the entrant depends on the research intensity of the incumbent, which reduces the probability of successful entry into this market. 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 might displace profits it already earns. Unlike many models, we do not assume the marginal productivity of the first atom of R&D investments are infinite. Thus expected returns must be sufficiently large for firms to justify an active R&D program.

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 this 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 younger and smaller 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 is very high, the entrant does not engage in R&D. In that case there is no strategic interaction, and the incumbent need only decide if the cost of R&D is less than the resulting expected incremental profits. 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 effect is dampened and the effect of rivalry is increased. This is all the more pronounced because additional R&D performed by the incumbent reduces the ex ante return to R&D for the entrant. 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. We use a number of other comparative statics from our model to determine when we can distinguish between other changes such as the magnitude of inventions and existing rents, the relative price of R&D, or the curvature of R&D cost function.

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

There are two firms: an incumbent (i) and a potential entrant (e). At the beginning of the game, the incumbent earns a profit $\pi > 0$ from its previous innovation. The entrant's current profits are normalized to zero. Both firms have access to a common stochastic R&D technology. Firm j chooses a probability of success θ_j, which costs $rf(\theta_j)$, where r is the price of R&D relative to final output. This cost function is assumed to be convex in effort.

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 is not an equilibrium outcome of the game.

2.1. Equilibrium Outcomes

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

$$\underset{\theta^e \in [0,1]}{Max} \{V^e = \theta_e(1-\theta_i)[\tilde{\pi} \ - b] - rf(\theta_e), 0\} \text{ and}$$

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

The associated first order conditions are

$$(1-\theta_i)[\tilde{\pi} \ - b] - rf'(\theta_e) = 0 \qquad \text{and} \qquad \tilde{\pi} - (1-\theta_e)\pi - rf'(\theta_i) = 0. \quad (1)$$

The second order conditions are simply:

$$|J| = r^2 f''(\theta_i)f''(\theta_e) + \pi[\tilde{\pi} \ - b] > 0.$$

Thus, if an interior equilibrium exists, it is unique and stable.

To be concrete, we will assume the R&D cost function takes the following form:

$$rf(\theta) = r\frac{(1-\theta)^{1-\phi} - 1}{\phi - 1}$$

Our assumptions about R&D costs are relatively general.[4] The model permits us to consider changes in the relative price of R&D, r, and its productivity, $f(\theta)$, allows us to explicitly vary the curvature of the cost function itself.[5] It turns out that a number of our comparative static results (see below) will turn on whether or not ϕ is larger or smaller than unity. We do not have a strong prior on the magnitude of this parameter, but we point out the following economic intuition: For values of $\phi \geq 1$, *the expected marginal cost of an R&D*

[4] Since $f(\theta)$ is monotonic in θ,it is clear we can invert this function and write the firm's problem in the form $g(y)\tilde{\pi} - ry$, where y represents units of R&D and $g(y) = \theta$. This is the form observed more often in the literatuer.

[5] In the Appendix, we explore an example with an additional fixed cost that is sunk at the time of the R&D decision.

failure $(f'(\theta)(1-\theta))$*is non-decreasing in research intensity.* Thus for relatively high values of ϕ,losing an intensive R&D contest is especially costly.

Finally note that the marginal cost of R&D as $\theta \to 0$ is $r > 0$. Since the first atom of R&D is not infinitely productive, and research productivity falls with increasing effort, the participation constraints are not trivial. Where R&D costs are relatively high, or the gross returns to R&D are relatively low, one or both firms will choose not to engage in R&D.

Using the first order conditions, and our cost function, we can derive an expression for the equilibrium value of the two firms:

$$\begin{aligned}\tilde{V}_e &= r\left\{\tilde{\theta}_e f'(\tilde{\theta}_e) - f(\tilde{\theta}_e)\right\} \\ \tilde{V}_i &= (1-\tilde{\theta}_e)\pi + r\left\{\tilde{\theta}_i f'(\tilde{\theta}_i) - f(\tilde{\theta}_i)\right\}\end{aligned}$$

2.1.1. R&D Reaction Functions

Rearranging the first order conditions, we can express each firm's choice of R&D intensity as a function of their rival's R&D intensity, which is take as given:

$$\widehat{\theta}_e = 1 - \left(\frac{r}{(1-\theta_i)[\tilde{\pi} \;\; - b]}\right)^{\frac{1}{\phi}} \qquad \text{and} \qquad \widehat{\theta}_i = 1 - \left(\frac{r}{\tilde{\pi} - (1-\theta_e)\pi}\right)^{\frac{1}{\phi}}.$$

It is immediately clear the entrant's reaction function is decreasing in the incumbent's R&D intensity while the incumbent's reaction function is increasing in the R&D intensity of the entrant (as long as $\pi > 0$).[6] At the extreme, the incumbent may be able to deter entry into R&D competition in the first place. More typically, the presence of an active entrant encourages the incumbent to do more R&D, since the likelihood the incumbent's R&D will only replace its existing profits is decreasing in the entrants probability of success.[7]

In the Appendix, we prove the following properties of the R&D reaction functions.

Proposition 1 *(a)* $\widehat{\theta}_e$ *is increasing in* $\tilde{\pi}$ *and decreasing in* r, ϕ *and* b; *(b) The slope of the entrant's reaction function* $(\partial\widehat{\theta}_e/\partial\theta_i)$ *is increasing in* $\tilde{\pi}$ *and decreasing in* r *and* b; *(c)* $\widehat{\theta}_i$ *is increasing in* $\tilde{\pi}$ *and decreasing in* r, ϕ *and* π; *(d) The slope of the incumbent's reaction function* $(\partial\widehat{\theta}_i/\partial\theta_e)$ *is decreasing in* $\tilde{\pi}$ *and increasing in* r *and* π.

[6] The entrant's reaction function is convex in θ_i while the incumbent's reaction function is concave in θ_e. Thus there is at most one intersection of the reaction functions.

[7] It is east to verify that in a duopoly with two entrants, the reaction functions are downard sloping.

The reaction functions also define the participation constraints for the two firms. To see this, find the level of the rival's R&D intensity that is consistent with an R&D intensity of 0 for the firm. Since the firm is assumed to be passive, one can then solve for the rival's R&D intensity as a function of the exogenous variables. In the Appendix, we prove the following:

Proposition 2 *(a) If $b < Min\{\hat{b}_e, \tilde{\pi} - r\}$,where $\hat{b}_e = \tilde{\pi} - r(\tilde{\pi} - \pi/r)^{\frac{1}{\phi}}$, the entrant engages in R&D; (b) If $\pi < \tilde{\pi} - r$,the incumbent engages in R&D; (c) If $\pi \geq \tilde{\pi} - r$, the incumbent engages in R&D only if $b < \hat{b}_i$,where $\hat{b}_i = \tilde{\pi} - r(\pi/\tilde{\pi} - r)^{\frac{1}{\phi}}$.*

Corollary 3 *If the above participation constraints are satisfied, there exists a unique interior equilibrium, characterized by the R&D intensities $(\tilde{\theta}_i, \tilde{\theta}_e) \in [0, 1]^2$.*

The participation constraints are illustrated in Figure 3 which collapses the parameter space into two dimensions (π, b) relative to $\tilde{\pi}$. 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, assuming the entrant is passive, the incumbent will not do any R&D if it costs more than the incremental gain in profits if successful, i.e. where $\tilde{\pi} - r - \pi \leq 0$ (also region I). The incumbent will always do R&D where this expression takes a positive sign (region II).

The more complicated participation constraints take into account the effect of an active competitor on the expected return to R&D. For example, the bottom half of region II consists of values of b where $\tilde{\pi} - b - r > 0$, and yet the entrant does not do R&D. In this region, the incumbent does a sufficient amount of R&D to discourage the entrant from engaging in R&D. But for even smaller values of b (region III), the entrant will do a positive amount of R&D even though the incumbent's R&D reduces the expected return from what it would be in the absence of competition with the incumbent. There is an opposite effect of R&D rivalry for the incumbent. Whereas he will not engage in R&D when the entrant is passive and $\tilde{\pi} - \pi - r \leq 0$, he will engage in R&D if the entrant is sufficiently active in her R&D (i.e. where $b < \hat{b}_i$ in the right hand portion of region III. More simply put, taking into account rival's R&D shifts the participation constraints of the two firms counter-clockwise, reducing the parameter space where the entrant is active, while increasing it for the incumbent.

The R&D intensity of the two firms can also be inferred from the distance of the actual parameters (π, b) from the constraints in the figure. Thus where b is small relative to π, the entrant is more R&D intensive than the incumbent (i.e. the area to the right of the dashed curve in region III). Conversely, where

b is large relative to π (i.e. the area to the left of this curve), the incumbent is more R&D intensive than the entrant.

2.1.2. Comparative Statics

In this section, we assume the participation constraints are satisfied strictly and examine how changes in the exogenous parameters affect the equilibrium R&D intensity and ex ante firm value of the entrant and incumbent. In general, we cannot solve for closed form solutions and so, in the Appendix, we derive many comparative static results.[8] The results reported here are also summarized in Table 1.

A number of results do not depend on the magnitude of ϕ:

Proposition 4 *(a) $\tilde{\theta}_e$ is decreasing in b and increasing in π; (b) $\tilde{\theta}_i$ is decreasing in b, π, r, and ϕ and increasing in $\tilde{\pi}$; (c) $\tilde{V}_e$ is decreasing in b and increasing in π; $\tilde{V}_i$ is increasing b and π.*

In general we can sign all the changes in the incumbent's R&D intensity. The R&D intensity of both firms move in the same direction as we change the cost of marketing capital (b), and in opposite directions when we change the level of existing profits (π). A robust result is that the entrant's value is decreasing b while the opposite is true for the incumbent. On the other hand, larger current profits raises the value of both firms because the incumbent competes less aggressively.

A number of other results depend on the magnitude of ϕ :

Proposition 5 *(a) If $\phi < 1$, $\tilde{\theta}_e$ and $\tilde{V}_e$ are increasing in r and decreasing in $\tilde{\pi}$, while $\tilde{V}_i$ is decreasing in r and increasing in $\tilde{\pi}$; (b) If $\phi > 1$, $\tilde{\theta}_e$ and $\tilde{V}_e$ are decreasing in r; (c) $\tilde{\theta}_e$ and $\tilde{V}_e$ are increasing in $\tilde{\pi}$ when $r\phi \geq [\tilde{\pi} - b]$.*

In the first case ($\phi < 1$), the entrant does better when the relative price of R&D (r) is higher and the gross return to innovation ($\tilde{\pi}$) is lower. This somewhat counterintuitive result follows from the fact that when ϕ is low, the incumbent's R&D intensity is especially responsive to changes in these parameters. As R&D becomes cheaper, or the benefits to innovation rise, the incumbent becomes much more aggressive in R&D, which results in a net decline in the entrant's R&D. This, in turn, increases the ex ante value of the incumbent and reduces the value of the ex ante value of the entrant.

The second case ($\phi > 1$), is more intuititive, at least for declines in the relative price of R&D. Here the incumbent strategy is less sensitive to changes in this parameter so that, on net, the entrant does more R&D and her market

[8] In the special case of $\phi = 1$, the cost function reduces to $\ln(1 - \theta)$ and we are able to derive closed form solutions.

value increases. But in the case of increases in $\tilde{\pi}$, ϕ must be sufficiently greater than 1 before it is clear the entrant benefits. Part (c) of the proposition provides a sufficient condition.

The final set of results pertain to changes in the ex ante value of the incumbent:

Proposition 6 *(a) $\tilde{V}_i$ is decreasing in r if $(\phi-1)^2\pi[\tilde{\pi}-b]-|J|\,[1-(1-\tilde{\theta}_i)^{\phi-1}]<0$; (b) $\tilde{V}_i$ is decreasing in ϕ if $\tilde{\theta}_i\,|J|\ln(1-\tilde{\theta}_i)+(1-\tilde{\theta}_i)\pi[\tilde{\pi}-b]\{\ln(1-\tilde{\theta}_i)-\phi\ln(1-\tilde{\theta}_e)\}<0$; (c) $\tilde{V}_i$ is increasing in $\tilde{\pi}$ if $\pi[\tilde{\pi}-b]+\tilde{\theta}_i r^2 f''(\tilde{\theta}_i)f''(\tilde{\theta}_e)-\pi r\phi(1-\tilde{\theta}_i)^{1-\phi}>0$.*

In general we cannot remove the endogenous variables from these conditions. Instead, we derive numerical solutions for particular values of the exogenous variables to characterize the implied constraints.[9] These are plotted in our parameter space diagram in Figure 4. Substituting different values of the parameters alters the position of these constraints, but has relatively little effect on their shape. For example, the first constraint implied in the proposition (for changes in r) is a nearly uniform displacement of the incumbent's participation constraint. Thus, so long as the incumbent is sufficiently R&D intensive in equilibrium, increasing the relative price of R&D will reduce the value of the firm. But if the incumbent is not doing much R&D in the first place, the primary effect of increasing r is to reduce the entrant's R&D, increasing the likelihood the incumbent will preserve his existing profits. A similar intuition applies to the second constraint (for changes in ϕ), although its shape is clearly different.[10]

2.1.3. Implications for Our Empirical Tests

While the complexity of these results might seem disadvantageous, we argue they reflect the generality of the model and economic intuition. The constraints on our ability to sign certain comparative statics tell us something important about how any structural hypotheses should be taken to the data. This is made more clear by examining Table 1, which illustrates changes in the exogenous parameters that consistent with our priors. Increases in π and $\tilde{\pi}$, for example, would be consistent with increasing market size or a productivity shock, respectively. Decreases in r and ϕ would be consistent with an increase in R&D productivity, possibly due to improvements in computers, and a decline to returns to scale in R&D, which might favor smaller firms.

The actual tests we run correspond to the first column of Table 1. The unshaded cells in the other columns of the table indicate where differences in the signs of the comparative statics of the model enable us to sort between

[9] This is done using the FindRoot command in Mathematica.

[10] We ignore the third constraint implied by the proposition (for changes in $\tilde{\pi}$), since it is nearly always satisfied if the first constaint is satisfied.

the effects of changes in the cost of marketing capital and a change in another parameter of the model. That does not mean we can always identify a particular alternative explanation. For example, the expected signs associated with an increase in $\tilde{\pi}$ or a decrease in r are almost identical. The cells that are shaded grey represent instances where we cannot distinguish between the effect of change in b or some other exogenous variable on the endogenous variable of interest. For example, when $\phi > 1$, the direction of change in R&D intensity induced by a fall in b is the same for a fall in r and nearly so for an increase in $\tilde{\pi}$. Finally, the cells shaded blue represent instances where we can distinguish the effect of decline in b on firm market values from a decrease in r or an increase in $\tilde{\pi}$ as long as the constraints specified in Proposition 6(a) and (c), respectively, are satisfied.

As Table 1 makes clear, it is easier to distinguish some exogenous changes than others. As long as $\phi \leq 1$, it is fairly easy to distinguish between the effects of changes in the cost of marketing capital and any of the other exogenous parameters. But we do not wish to rule out more curvature a priori. Nor does our data give us clear evidence about the magnitude of ϕ. It becomes more difficult, however, to distinguish the effects of changes in b from changes in changes $\tilde{\pi}$, r, or ϕ when $\phi > 1$. For ϕ, identification relies on differences in the expected changes in the reaction functions and R&D intensity. For $\tilde{\pi}$ and r identification relies primarily on differences in the expected changes in firm market value. In that case, identification also requires that the assumptions in Proposition 6 are satisfied. In other words, we must focus on industries that were already sufficiently R&D intensive prior to the decline in the cost of marketing capital in late 1970s. In particular, the incumbent firms must be sufficiently R&D intensive ex ante. It may well be the case that the mechanism we describe in this paper also explains behavior outside such R&D intensive industries but careful analysis of the model shows we can not easily distinguish this mechanism from a number of competing explanations.

2.1.4. Accounting for entry by more than one firm

Of course a duopoly model may not be sufficient to characterize all the effects of falling barriers to entry over time. In the appendix, we present an example where we generalize the model to allow for the possibility of entry by more than one firm.[11] We do this by adding a second fixed cost (c) that entrants must sink just prior to engaging in R&D. This cost could be interpreted as a fixed cost of establishing an R&D program. But it could also represent any of a number of lumpy costs borne by firms before the uncertain outcome of their R&D is resolved. It is the timing of this fixed cost which distinguishes it from marketing capital, which is sunk after the invention process has reached its conclusion.

[11] To keep things as simple as possible in this example, we assume $\phi = 1$ so that we can derive closed form solutions.

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 as narrowly as we can. 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.[12] 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 (see Table 2). We call these R&D industries.[13]

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).[14] We identify 68 of these firms spread across 28 R&D industries (see Table 3).[15] 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 4). 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 (Chandler 1994). 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.

We include some additional variables in some our regressions. The first is a measure of the patent intensity of firms and their competitors. This variable may be useful as a control for changes in the productivity of R&D, but also for changes in U.S. intellectual property law, which might possibly have influenced the ability of smaller firms to enter markets.[16] The intuition

[12] For firms in existence for a considerable period of time, we use the SIC code assigned to the firm in the 1987 or 1988 vintages of Compustat. Thus, in our tabulations IBM is a manufacturer of computers and not a software company.

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

[14] 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.

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

[16] We thank Wesley Cohen for suggesting we explore this possibility in our data.

here is that "strengthening" intellectual property rights may facilitate markets for technology and access to venture capital funds, and this may increase the ex ante return to R&D for younger and smaller firms.[17] Separately, we know there has been a significant increase in patenting rates in the U.S. over the last quarter century (Hall 2003). If this has affected the nature of competition between large and small firms, we should control for it.

At the firm level, we construct a measure of patent intensity by taking the sum of the patents obtained in the previous five years and normalizing by a one year lag of the operating expenses of the firm, adjusted for inflation. We construct an analogous intensity for the firms' rivals in the same industry by taking the sum of patents obtained by those firms in the preceding five years and dividing by the sum of their inflation adjusted operating expenses in the previous year. The patent data is obtained by matching our firms to those found in the NBER Patent Citations Data file (Hall, Jaffe, and Trajtenberg 2001). Not all of our firms are found in the that file, however, and so we check for selection bias when estimating regressions using these variables.

Another concern is that the nature of R&D competition may depend the degree of industry concentration, which varies over time. To the extent that our fixed effects regressions do not address changes in competitive conditions in the industry, our results could be sensitive to omitted variable bias. To check for this possibility, we assembled data on the concentration of shipments (or revenues) from the Census of Manufacturers and Services. These data exist at five year intervals, so we linearly interpolate between the census years.[18] Unfortunately, concentration ratios are not available for all industries, so we will lose many observations when including these variables in our regressions.

Finally, an additional source of identification might be obtained by exploiting variations in the rate of computer adoption across industries. One way to explore this possibility is to construct a measure of the intensity of computer use by workers in the industry in at least one period of time. In this paper, we use data from the March 1984 edition of the Current Population Survey which asked workers whether they use a personal computer at work. This is the first year such a question was asked. Our intensity measure is simply the sum of full time workers in an industry answering "yes" to that question, divided by the total number of full time workers surveyed in that industry in 1984.

4. Empirical Results

We evaluate our data in the following order: (1) changes in R&D intensities, (2) shifts in the R&D reaction functions, and (3) changes in market value.

[17] For empirical evidence of the significance of such a channel in the chemical industry, see Arora, Fosfori, and Gamerdella (2001)

[18] Matching industries in the Census data to our industry definitions is not always perfect. Details on how we assemble these variables are available from the authors.

4.1. *Trends in Firm R&D Intensity*

We turn first to the patterns in R&D intensity among the various categories of firms defined in the previous section. According to our model, as the cost of marketing capital falls, entrants should perceive the incumbent's markets as more vulnerable and increase their investments in R&D. We expect incumbents to respond by increasing their R&D intensity.

Table 4 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 70 percent; thereafter it declined.[19]

Second, 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 5 documents the distinct rise in R&D intensity of U.S. non-incumbent firms over time. It was significantly higher in 1999 than in 1974 for non-incumbent firms whether in computer industries, incumbent industries, or non-incumbent industries (the p values for the F statistics are all less than 0.01). In the noncomputer industries, incumbent firms also increase their R&D (again the p value is less than 0.01). In contrast, in the computer industries, the five incumbents begin with the highest R&D intensity, but actually have a lower R&D intensity by 1999.

In 1974, incumbent firms had an R&D intensity higher than the R&D intensity of non-incumbent firms. This was true for incumbents in both the computer and non-computer sectors (p values for the 1-sided test of 0.006 and 0.042, respectively). By 1999, however, the incumbent firms have lower R&D intensities than non-incumbents in the same industries, but the difference between them is at best marginally significant – at the one-sided 10 percent level for the computer industries, and not significantly different for the other industries. Thus we have clear evidence that non-incumbent firms switched from lower R&D intensities to at least equal R&D intensities over this period.

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

In summary, the patterns we observe for R&D intensities are consistent with the model's predictions for a decline in the cost of marketing capital. This should rule out changes in the current rents earned by incumbents, or an increase in the curvature of the R&D cost function, as plausible explanations.[20] But to rule out the other explanations, we need to test some additional implications of the model.

4.2. R&D Reaction Functions

Next, we analyze how research and development expenditures and firm market value were affected by changes in the cost of marketing capital. 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.

We proxy for the declining cost of marketing capital with a variable that reflects the falling cost of computing power over time, using its dual, the rate of investment in computer hardware.[21] To be explicit, we use the ratio of nominal business fixed investment in computers and peripheral equipment to nominal gross domestic product. We will call this variable $Comp_t$. This ratio has risen over time (Figure 4).

Our reaction functions take the following form. All financial variables, including R&D, are normalized by operating expenses. Let $R\&D^i_{j,t}$, denote the ratio of R&D to operating expense for firm i, in industry j, in time t. Let $R\&D^{\tilde{i}}_{j,t}$ denote the aggregate R&D intensity of its rivals in the same industry where

$$R\&D^{\tilde{i}}_{j,t} \equiv \frac{\sum\limits_{k\neq i} R\&D^k_{j,t}}{\sum\limits_{k\neq i} OpExp^k_{j,t}}.$$

We regress the firm's R&D intensity on a lag of its rival R&D intensity, a firm effect, and a complete set of year dummies. We also include in the regression an interaction of the rival R&D intensity and our proxy for the falling cost of marketing capital, both lagged.[22] The basic regression is thus:

$$R\&D^i_{j,t} = \alpha_0 + \alpha_1 * R\&D^{\tilde{i}}_{j,t-1} + \alpha_2 * comp_{t-1} * R\&D^{\tilde{i}}_{j,t-1} + u_i + v_t + \epsilon_{it} \quad (2)$$

[20] Note that these patterns do not rule out a *decrease* in the curvature of the R&D cost function (see Table 1).

[21] The relationship between the ubiquity of computing power and its affect on marketing capital is discussed in the introduction.

[22] The results are essentially the same when we instead use contemporaneous values of these variables.

We will be interested in the possible effects of a technology shock or a change in the productivity of R&D, which may affect $\tilde{\pi}$ or r, respectively. So we also construct two additional variables in a manner similar to our R&D variables. The first is the market value of the firm's rivals in the industry, $MV_{j,t}^{\tilde{i}}$.[23] The second is a count of the number of patents obtained in the last 5 years by the firm's rivals in the industry, $Pat_{j,t}^{\tilde{i}}$. Both of these variables are normalized by their operating expenses of the rival firms. We perform these regressions on the set of R&D-intensive industries as a whole and four main subsets. We have 4,153 firms in all, averaging about 8 annual observations per firm. Table 6 presents descriptive statistics for the firms in our data set.

Table 7 presents the most parsimonious specification of the reaction function regressions. Taking all firms together, we see the coefficient on the interaction of rival R&D intensity and the computer share variable is about 0.4, a value that is both economically and statistically significant. The *comp* variable rises from 0.2 to 1.0 between 1973 to 1997, so the net effect of rivals' R&D intensity 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. 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. We therefore separate these industries from the non-computer industries. Still, the pattern for the computer industry does not look all that different than for R&D industries as a whole.

For the R&D industries outside of computers, 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 different interaction between the long-term incumbents and their rivals than in the industries without incumbent firms. What we find is much higher degree of strategic interaction in the industries with incumbent firms, and this strategic interaction increased as computing power became more ubiquitous. For long-term incumbents, the coefficient on rivals' R&D is 0.83, which is clearly larger than the response of other firms in the same industries. Since rivals' R&D has a "within" standard deviation that is two-

[23] This is calculated as the number of shares outstanding at the end of the year times end-of-year price

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 intensity, the reaction is still larger than what is observed among firms in industries without long-term incumbents.

The substantial shift in the reaction functions of non-incumbent firms as investment in computers rose is consistent with the testable implications for a reduction in the cost of marketing capital implied by the model. The fact that the incumbent's reaction function has also changed suggests either (1) incumbents are also sinking investments in marketing capital, or (2) other factors have also changed.[24] The leading candidates for alternative explanations are an increase in the rents associated with new inventions or an increase in the productivity of R&D. To test for the effects of an increase in rents from new innovations, we add to the specification in (2) lagged values of the market value of the firm, and of its competitors in the same industries, plus interactions with rival R&D intensity to identify shifts in the reaction function driven by such changes.[25] Market value is a forward looking variable and should be correlated with the economic opportunities available to firms in an industry. And improved prospects for an industry may result in an intensification of R&D competition. The results are shown in the first part of Table 8.

The first thing to note is that the coefficients on the interactions variable estimated in Table 7 have become larger, and even more precisely measured. Where the coefficients are significant (for non-incumbent firms), higher values of the firm's own market value is associated with a higher R&D intensity, while higher values for the firm's rivals are associated with less R&D (for firms in incumbent industries). Thus it does appear that the market value variables are picking up the opportunities available to firms, as well as the opportunities available to their rivals, which are likely to erode s profits. The interaction of rival market value and rival R&D is significant only for non-incumbents, and takes different signs–it is positive in incumbent industries but negative in the other industries. Thus changes in economic opportunities appears to have shifted the reaction function of firms. Nevertheless, the effect of ubiquitous computing power on the firms' reaction functions remains.[26]

To examine the second possibility, changes in the productivity of R&D, we add to the specification in (2) lagged values of the patent intensity of the firm and its rivals, plus interactions of these variables with rival R&D intensity. These variables may also pick any changes in intellectual property

[24] This is consistent with a generalization of the model where the incumbent must also sink investments in marketing capital to deploy a new innovation, but need not spend as much as the entrant.

[25] Again, market value is normalized by operating expenses.

[26] This conclusion also follows from regressions (not shown) that allow for a complete set of interactions between the market value, R&D, and the computer investment variables.

law that could affect the attractiveness of investments in R&D. Results are reported in the middle columns of Table 8. The qualitative properties of the original variables are essentially the same, although there is a change in sign for the initial slope of the incumbent's reaction function. A higher own patent intensity is associated with a higher R&D intensity, at least for non-incumbent firms. This would be consistent with the testable implications for a decline in the real cost of R&D. For non-incumbents, larger values of rival patent intensity are associated with less R&D, which is consistent with the entry deterrence mechanism of the model when competitors gain an advantage in R&D. The interactions with rival R&D are only significant for firms outside the incumbent industries and are difficult to interpret.[27]

Earlier we raised the possibility of confusing increased strategic interaction in more concentrated industries with the effects of declining computing costs on the cost of marketing capital. In principal our fixed effects specification, year dummies, and separate treatment of incumbent and non-incumbent industries should control for such phenomenon. Additional assurance can be obtained by including measures of industry concentration in our regressions, as we report in the final set of columns in Table 8. Again, the coefficients on the main variables of interest remain qualitatively the same. Interestingly, higher concentration is associated with somewhat higher R&D intensity among incumbent firms, and somewhat less among firms in non-incumbent industries. On the other hand, the effect of R&D competition on an incumbent's R&D intensity is somewhat attenuated by the overall concentration of the industry.

All in all, the reaction function regressions appear quite robust and the results are consistent with a decline in the cost of marketing capital. As an additional check, we divided our data set into two groups of industries based on the degree to which their employees were early adopters of the personal computer. We did this using data from the March 1984 Current Population Survey, which was the first to ask individuals if they used a PC at work. Across all industries, approximately 40 percent of full time workers indicated they were already using a PC at work. We coded CPS industries into "early" or "late" adopters depending on whether the PC utilization rate was above or below this mean value. We then mapped the CPS industries into our R&D industries.[28] We then re-ran our regressions separately for firms in the early and late adoption industries.

Results are reported in Table 9. When looking across all industries, the results are indeed strong among the early adoption group. In addition, the within R^2 is higher in the regressions for this group. The coefficients estimated for incumbent firms are much larger and more precisely measured. For non-incumbents in incumbent industries, the results are fairly similar. Among the non-incumbent industries, however, the estimates are more precise for firms in

[27] As with the the market value variables, including a complete set of interactions of the patent variables does not alter the qualitative results shown in the tables.

[28] Details of these steps are found in a separate data appendix.

the industries that were late adopters.

4.3. 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.

The empirical exercise is to decompose the value of firms into three components: the net value of their tangible assets, the value of their investments in R&D, and the value of their patents. The latter reflects past investments in R&D and its productivity, but it also takes into account any incremental contribution to firm value that patents confer by virtue of increasing the ability of the firm to appropriate rents from its innovations. We then interact these variables with our proxy for the declining cost of marketing capital to see how the value of firms change.

As with our R&D regressions, our variables are normalized by the operating expenses of the firm. The regression (implicitly) includes fixed firm effects and (explicitly) includes industry specific year effects (see below):

$$\begin{aligned} MV^i_{j,t} &= \beta_0 + \beta_1 * comp_{t-1} + \beta_2 * BV^i_{j,t-1} + \beta_3 * R\&D^i_{j,t-1} \\ &\quad + \beta_4 * comp_{t-1} * R\&D^i_{j,t-1} + \beta_5 Pat^i_{j,t-1} + \beta_6 * comp_{t-1} * Pat^i_{j,t-1} \\ &\quad + u_i + v_{j,t} + \epsilon_{it} \end{aligned}$$

This specification permits us to identify a direct effect of our proxy variable on market value as well as to better control for variation in the valuation of companies across industries.

Unlike with our reaction function regressions, we must control for selection bias in this regression. The problem is that not all firms in our data set are matched to their patents in the NBER Patents Citation Data File and the matches themselves are not random. In general larger, older, more research intensive firms are more likely to be matched to their patents (see Hall, Jaffe and Trajtenberg 2001). To correct for the possibility of biased coefficients, we first demeaned our data set (to allow for a fixed effect) and then estimated our equation using a two stage procedure. In the first stage, the probability a firm is matched to its patents is estimated using data on firm size (assets and R&D), a dummy variable for firms in the first five years of their appearance in Compustat, and a complete set of year dummies. We estimate our second stage regression, incorporating the Mills Ratio derived from this first stage.[29] Results are reported in Table 10.

The increasing ubiquity of computers has three effects on the market's valuation of incumbent firms. First, there is a very large negative direct effect. At the same time, there is a large, positive effect on the valuation of R&D investments among incumbent firms. Finally, there is significant, negative effect on the market valuation of patents recently obtained by incumbents. This stands in contrast to other firms in the incumbent industries, who benefit primarily from an increase in the market's valuation of their recently obtained patents. For firms in industries without incumbent firms, the dynamics appear to be rather different. The primary effect of increased computerization is a large, negative shock to the valuation of the firm's physical assets, net of any outstanding debt.

Table 11 presents the marginal effects (expressed as elasticities) implied by the regressions in Table 10, evaluated at the means of the independent variables in 1995.[30] Thus a one percentage point increase in the ratio of computer investment to GDP is associated with a 2.4 percent decline in the market value of incumbent firms. The implied effects for non-incumbents are an order of magnitude smaller. Among incumbent firms, 70 percent of the increase in the market valuation of R&D investments is offset by a decline in the valuation of the firms' patents, a measure of the successful previous R&D investments made by these firms. The final row of Table 3 calculates the change in the market value of firms implied by a 1 percent increase in the ratio of computer investment to GDP. For incumbent firms, the effect is sizeable - a loss of about $17 billion in value.

How do these results square with the implications of our model? Clearly the dynamics are more complex than the simplest versions presented in the text. But the results are quite consistent with more general versions of the model. For example, the effects of a decline in b in an industry without an established incumbent is ambiguous. On the one hand, the ex ante value of firms contemplating entry may rise, as long as there is not so much entry these rents are entirely dissipated. For young firms that have already entered, however, the effects of a decline in the cost of marketing capital are very likely negative since they will encounter yet more competition from potential entrants. In the incumbent industries, young firms face these pressures, but they also benefit from an improvement in their competitive position vis-a-vis incumbent firms, who are now less effective in deterring entry. As predicted by the model, the value of incumbent firms decline, but this is partially offset by an increase in the value of R&D among these firms. That is consistent with a decline in the importance of the replacement effect since, on average,

[29] Hausman tests (not shown) verify that our market value regressions are sensitive to selection bias, but our reaction function regressions (incorporating patent variables) are not.

[30] The effects would be smaller if we calculated these effects for an earlier year.

and incumbent's R&D is *relatively* less likely to replace its current rents and *relatively* more likely to preclude successful entry by new firms.[31] In other words, incumbent firms that are willing to race harder, all else equal, will be more successful in maintaining their competitive advantage.

Finally, the sign of the coefficients on the interactions for the firms' patents in incumbent industries are consistent with a version of the model (not shown) that permits the incumbent to make a licensing offer to the entrant before she sinks b. In that case, the terms of trade depend on the magnitude of the cost of marketing capital and declines in this cost work in favor of entrants in incumbent industries. This option is not available, however, where an incumbent does not exist.

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 incumbent firms fell, but this was offset in part by an increase in the valuation of R&D among incumbent firms, which we attribute to the declining importance of the replacement effect among these firms. The value of entrant firms in incumbent industries increased, it appears, because of an improvement in the terms of trade in their licensing negotiations with large, established firms. In the non-incumbent industries, there was a slight decline in market value, which is likely attributable to increased dissipation of rents resulting from significant entry by many new firms.

All in all, the empirical tests support the implications of our model. Clearly many factors are driving changes in the nature and intensity of R&D competition among firms in the U.S. economy. But we conclude that an essential part of the story is a decline in fixed costs firms sink after they innovate, but before they reach the final markets for their goods and services. In the past, substantial investments in the marketing capital tended to protect large, established firms. This appears to be much less the case today and the net affect has been more entry by R&D intensive firms and an increase in the aggregate R&D intensity of the U.S. economy.

[31] This is true even though, in absolute terms, the incumbent is less effective in deterring entry,

References

Aghion, Phillipe, Nicholas Bloom, Richard Blundell, Rachel Griffith, and Peter Howitt, "Competition and Innovation: An Inverted U Relationship," NBER Working Paper No. 9269, October 2002.

Arora, Ashish, Andrea Fosfori, and Alfonso Gambardella. *Markets for Technology.* Boston: MIT Press (2001).

Bernstein, Jeffrey I. and M. Ishaq Nadiri, "Research and Development and Intra-Industry Spillovers: An Empirical Application of Dynamic Duality," *Review of Economic Studies* 56, April 1989, 249-267.

Bils, Mark and Peter Klenow, "The Acceleration in Variety Growth," *American Economic Review* 91, May 2001, pp. 274-280.

Bloom, Nicholas, Mark Schankerman, and John Van Reenan, "Identifying Technology Spillovers and Product Market Rivalry," CEPR Working Paper No. 4912, February 2005.

Campbell, John Y., Martin Lettau, Burton G. Malkiel, and Yexaio Xu, "Have Individual Stocks Become More Volatile? An Empirical Exploration of Idiosyncratic Risk," *Journal of Finance* 56, February 2001, 1-43.

Capital and Related Measures from the Two Digit Database, 1949 to 2002. Washington, DC: Bureau of Labor Statistics, 2005.

Chandler, Alfred D., Scale and Scope: The Dynamics of Industrial Capitalism. Belknap Press, Cambridge MA, reprint edition, 1994.

Cockburn Iain, and Rebecca Henderson, "Racing To Invest? The Dynamics of Competition in Ethical Drug Discovery," *Journal of Economics & Management Strategy* 3, Fall 1994, 481-519.

Comin, Diego, and Thomas Philippon, "The Rise in Firm-Level Volatility: Causes and Consequences," NBER Working Paper No. 11388, May, 2005.

Grabowski, Henry G., and Nevins D. Baxter, "Rivalry in Industrial Research and Development," *Journal of Industrial Economics* 21, July 1973, 209-235.

Greenwood, Jeremy, and Boyan Jovanovic, "The IT Revolution and the Stock Market," *American Economic Review Papers and Proceedings* 89, May 1999, 116-22.

Hall, Bronwyn, "The Stock Market Value of R&D Investment During the 1980s," *American Economic Review* 83, (1993), 259-264.

Hall, Bronwyn, "Industrial Research During the 1980s: Did the Rate of Return Fall?" Brookings Papers on Economic Activity, Microeconomics 2, 1993, pp. 289-344.

Hall, Bronwyn H. "Exploring the Patent Explosion," invited lecture at the ZEW Workshop on Empirical Economics of Innovation and Patenting, Mannheim, Germany, (March 14/15, 2003).

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

Hall, Bronwyn and Daehwan Kim, "Valuing Intangible Assets: The Stock Market Value of R&D Revisited," mimeo, Nuffield College, Oxford University, 2000.

Hayashi, Fumio, "Tobin's Marginal q and Average q: A Neoclassical Interpretation," *Econometrica* 50, January 1982, pp. 213-224.

Huson, Mark R., Robert Parrino, and Laura T. Starks, "Internal Monitoring Mechanisms and CEO Turnover: A Long-Term Perspective," *Journal of Finance* 56, December 2001, 2265-2297.

Jovanovic, Boyan, and Peter Rousseau, "Vintage Organizational Capital," NYU Working Paper, 2001.

Lev, Baruch, and Theodore Sougiannis, "The Capitalization, Amortization, and Value Relevance of R&D," *Journal of Accounting and Economics* 21, February 1996, 107-138.

Scherer, Frederic M., and Dietmar Harhoff, "Technology Policy for a World of Skew-distributed Outcomes," *Research Policy* 29, 559-566, 2000.

Stein, Jeremy C., "Waves of Creative Destruction: Firm-Specific Learning-by-Doing and the Dynamics of Innovation," *Review of Economic Studies* 64, April 1997, 265-288.

6. Appendix

6.1. Results in the Text

Proposition 1

Proof. Parts (a) and (c) follow from the derivatives of the reaction function with respect to b, π, $\tilde{\pi}$,r,and ϕ, holding constant the rival's R&D intensity:

$$\frac{\partial\hat{\theta}_e}{\partial b} = \frac{-(1-\hat{\theta}_e)}{\phi(\tilde{\pi}-b)} \qquad \frac{\partial\hat{\theta}_i}{\partial b} = 0$$

$$\frac{\partial\hat{\theta}_e}{\partial \pi} = 0 \qquad \frac{\partial\hat{\theta}_i}{\partial \pi} = \frac{-(1-\theta_e)(1-\hat{\theta}_i)}{\phi[\tilde{\pi}-(1-\theta_e)\pi]}$$

$$\frac{\partial\hat{\theta}_e}{\partial \tilde{\pi}} = \frac{(1-\hat{\theta}_e)}{\phi(\tilde{\pi}-b)} \qquad \frac{\partial\hat{\theta}_i}{\partial \tilde{\pi}} = \frac{(1-\hat{\theta}_i)}{\phi[\tilde{\pi}-(1-\theta_e)\pi]}$$

$$\frac{\partial\hat{\theta}_e}{\partial r} = \frac{-(1-\hat{\theta}_e)}{r\phi} \qquad \frac{\partial\hat{\theta}_i}{\partial r} = \frac{-(1-\hat{\theta}_i)}{r\phi}$$

$$\frac{\partial\hat{\theta}_e}{\partial \phi} = \frac{(1-\hat{\theta}_e)\ln(1-\hat{\theta}_e)}{\phi^2} \qquad \frac{\partial\hat{\theta}_i}{\partial \phi} = \frac{(1-\hat{\theta}_i)\ln(1-\hat{\theta}_i)}{\phi^2}$$

Parts (b) and (d) are derived in the same way, but after taking the derivative of the reaction function with respect to the rival's R&D intensity:

$$\frac{\partial^2\hat{\theta}_e}{\partial\theta_i\partial b} = \frac{-(1-\hat{\theta}_e)}{\phi^2(1-\theta_i)(\tilde{\pi}-b)} \qquad \frac{\partial^2\hat{\theta}_i}{\partial\theta_e\partial b} = 0$$

$$\frac{\partial^2\hat{\theta}_e}{\partial\theta_i\partial \pi} = 0 \qquad \frac{\partial^2\hat{\theta}_i}{\partial\theta_e\partial \pi} = \frac{(1-\hat{\theta}_i)[\phi\tilde{\pi}+(1-\theta_e)\pi]}{\phi^2[\tilde{\pi}-(1-\theta_e)\pi]}$$

$$\frac{\partial^2\hat{\theta}_e}{\partial\theta_i\partial \tilde{\pi}} = \frac{(1-\hat{\theta}_e)}{\phi^2(1-\theta_i)} \qquad \frac{\partial^2\hat{\theta}_i}{\partial\theta_e\partial \tilde{\pi}} = \frac{-(1-\hat{\theta}_i)\pi(1+\phi)}{\phi^2[\tilde{\pi}-(1-\theta_e)\pi]}$$

$$\frac{\partial^2\hat{\theta}_e}{\partial\theta_i\partial r} = \frac{-(1-\hat{\theta}_e)}{r\phi^2(1-\theta_i)} \qquad \frac{\partial^2\hat{\theta}_i}{\partial\theta_e\partial r} = \frac{(1-\hat{\theta}_i)\pi}{r\phi^2[\tilde{\pi}-(1-\theta_e)\pi]}$$

$$\frac{\partial^2\hat{\theta}_e}{\partial\theta_i\partial \phi} = \frac{(1-\hat{\theta}_e)[\ln(1-\hat{\theta}_e)+\phi]}{\phi^3(1-\theta_i)} \qquad \frac{\partial^2\hat{\theta}_i}{\partial\theta_e\partial \phi} = \frac{-(1-\hat{\theta}_i)\pi[\ln(1-\hat{\theta}_i)+\phi]}{\phi^3[\tilde{\pi}-(1-\theta_e)\pi]}$$

Note that the derivatives with respect to ϕ cannot be signed a priori. ■

Proposition 2 and Corollary 3

Proof. First we derive the participation constraints characterized by the expressions $\hat{b}_e$ and $\hat{b}_i$ in the text. These follow from the R&D reaction functions implied by the first order conditions. First, set $(1-\hat{\theta}_e) = 1$ and solve for the *minimum* value of θ_i where the entrant's best response is to be passive. This implies that $(1-\theta_i) \leq r/[\tilde{\pi}-b]$. We compare this expression to the one implied by the reaction function for the incumbent when the entrant is passive: $(1-\hat{\theta}_i) = (r/[\tilde{\pi}-\pi])^{\frac{1}{\phi}}$. Setting these two expression equal to each other, we can derive a critical value of b as a function of π and the other exogenous parameters of the model: $\hat{b}_e = \tilde{\pi} - r([\tilde{\pi}-\pi]/r)^{\frac{1}{\phi}}$.

Similarly, we can set $(1-\hat{\theta}_i) = 1$ and solve for the *maximum* value of θ_e where the incumbent's best response is to be passive. This implies that $(1-\theta_e) \geq [\tilde{\pi}-r]/\pi$. We compare this expression to the one implied by the reaction function for the entrant when the incumbent is passive: $(1-\hat{\theta}_e) =$

$(r/[\tilde{\pi}-b])^{\frac{1}{\phi}}$. Setting these two expressions equal to each other, we can derive the analogous critical value of b: $\hat{b}_i = \tilde{\pi} - r(\pi/[\tilde{\pi}-r])^{\phi}$.

To demonstrate existence and uniqueness of an interior equilibrium, assume the exogenous parameters are such the participation constraints characterized by $\hat{b}_e$ and $\hat{b}_i$ are satisfied. Using the entrant's reaction function, substituting for $(1-\theta_i)$ using the incumbent's reaction function, and rearranging terms, we arrive at the following expression:

$$\frac{(1-\theta_e)^{\phi}}{[\tilde{\pi}-(1-\theta_e)\pi]^{\frac{1}{\phi}}} = \left(\frac{1}{\tilde{\pi}-b}\right) r^{\frac{\phi-1}{\phi}}. \tag{A1}$$

For $\tilde{\pi}-b>0$, the right hand side of (A1) is positive and finite. The left hand side decreases monotonically, and is continuous, in θ_e. Taking the limit as $\theta_e \to 1$,the left hand side converges to zero. The limit as $\theta_e \to 0$ is $(\tilde{\pi}-\pi)^{\frac{-1}{\phi}}$. As long as this expression is larger than the right hand side of __ (which follows if $b \le \hat{b}_i$), we know $\exists!\ \tilde{\theta}_e \in [0,1]$ where the equality in (A1) is satisfied

■

The other results follow from the comparative static properties of the system of equations:

$$\begin{aligned}
\frac{\partial V_e}{\partial \theta_e} &= (1-\theta_i)\,[\tilde{\pi}-b] - r(1-\theta_e)^{-\phi} \\
\frac{\partial V_i}{\partial \theta_i} &= \tilde{\pi} - (1-\theta_e)\pi - r(1-\theta_i)^{-\phi}
\end{aligned}$$

with the associated Jacobean $|J| = r^2 f''(\theta_i) f''(\theta_e) + \pi[\tilde{\pi}\ -b] > 0$.The comparative static derivatives for R&D intensities are:

$$\frac{\partial \tilde{\theta}_e}{\partial x} = |J|^{-1}\left\{ r f''(\theta_i)\frac{\partial^2 V_e}{\partial \theta_e \partial x} - [\tilde{\pi}-b]\,\frac{\partial^2 V_i}{\partial \theta_i \partial x}\right\}$$

and

$$\frac{\partial \tilde{\theta}_i}{\partial x} = |J|^{-1}\left\{ r f''(\theta_e)\frac{\partial^2 V_i}{\partial \theta_i \partial x} + \pi\frac{\partial^2 V_e}{\partial \theta_e \partial x}\right\}$$

where $x \in \{b, \pi, \tilde{\pi}, r, \phi\}$.

The associated partial derivatives of the value functions are:

$$\frac{\partial^2 V_e}{\partial\theta_e\partial b} = -(1-\theta_e) \qquad \frac{\partial^2 V_i}{\partial\theta_e\partial b} = 0$$
$$\frac{\partial^2 V_e}{\partial\theta_e\partial\tilde{\pi}} = (1-\theta_i) \qquad \frac{\partial^2 V_i}{\partial\theta_i\partial\tilde{\pi}} = 1$$
$$\frac{\partial^2 V_e}{\partial\theta_e\partial\pi} = 0 \qquad \frac{\partial^2 V_i}{\partial\theta_i\partial\pi} = -(1-\theta_e)$$
$$\frac{\partial^2 V_e}{\partial\theta_e\partial r} = -f'(\theta_e) \qquad \frac{\partial^2 V_i}{\partial\theta_i\partial r} = -f'(\theta_i)$$
$$\frac{\partial^2 V_e}{\partial\theta_e\partial\phi} = rf'(\theta_e)\ln(1-\theta_e) \qquad \frac{\partial^2 V_i}{\partial\theta_i\partial\phi} = rf'(\theta_i)\ln(1-\theta_i)$$

Proposition 4

Proof. Part (a) follows from the derivatives

$$\frac{\partial\tilde{\theta}_e}{\partial b} = \frac{-r\phi}{|J|}f'(\tilde{\theta}_i) \qquad \text{and} \qquad \frac{\partial\tilde{\theta}_e}{\partial\pi} = \frac{1}{|J|}(1-\tilde{\theta}_e)[\tilde{\pi}-b].$$

Part (b) follows from the derivatives

$$\frac{\partial\tilde{\theta}_i}{\partial b} = \frac{-1}{|J|}(1-\tilde{\theta}_i)\pi; \qquad \frac{\partial\tilde{\theta}_i}{\partial\pi} = \frac{-r\phi}{|J|}f'(\tilde{\theta}_e);$$
$$\frac{\partial\tilde{\theta}_i}{\partial\tilde{\pi}} = \frac{1}{|J|}[rf''(\tilde{\theta}_e)+(1-\tilde{\theta}_i)\pi]; \qquad \frac{\partial\tilde{\theta}_i}{\partial r} = \frac{-f''(\tilde{\theta}_e)}{\phi\,|J|}[\phi\tilde{\pi}+(1-\phi)(1-\tilde{\theta}_e)\pi];$$

and

$$\frac{\partial\tilde{\theta}_i}{\partial\phi} = \frac{rf''(\tilde{\theta}_e)}{\phi\,|J|}\{\phi[\tilde{\pi}-(1-\tilde{\theta}_e)\pi]\ln(1-\tilde{\theta}_i)+(1-\tilde{\theta}_i)\pi\ln(1-\tilde{\theta}_e)\}.$$

Part (c) follows from the derivatives

$$\frac{\partial\tilde{V}_e}{\partial b} = r\tilde{\theta}_e f''(\tilde{\theta}_e)\frac{\partial\tilde{\theta}_e}{\partial b}; \qquad \frac{\partial\tilde{V}_e}{\partial\pi} = r\tilde{\theta}_e f''(\tilde{\theta}_e)\frac{\partial\tilde{\theta}_e}{\partial\pi};$$
$$\frac{\partial\tilde{V}_i}{\partial b} = r\tilde{\theta}_i f''(\tilde{\theta}_i)\frac{\partial\tilde{\theta}_i}{\partial b} - \pi\frac{\partial\tilde{\theta}_e}{\partial b} = \frac{r\phi}{|J|}f'(\tilde{\theta}_i)(1-\tilde{\theta}_i)\pi;$$

and

$$\frac{\partial\tilde{V}_i}{\partial\pi} = r\tilde{\theta}_i f''(\tilde{\theta}_i)\frac{\partial\tilde{\theta}_i}{\partial\pi} - \pi\frac{\partial\tilde{\theta}_e}{\partial\pi} + (1-\tilde{\theta}_e) = \frac{r^2}{|J|}f''(\tilde{\theta}_i)f''(\tilde{\theta}_e)(1-\tilde{\theta}_i).$$

■

Proposition 5

Proof. The results for changes in (r) follow from the derivatives:

$$\frac{\partial\tilde{\theta}_e}{\partial r} = \frac{rf''(\tilde{\theta}_e)f''(\tilde{\theta}_i)}{\phi\,|J|}(1-\phi) \qquad \textit{and} \qquad \frac{\partial\tilde{V}_e}{\partial r} = \frac{\tilde{V}_e}{r} + r\tilde{\theta}_e f''(\tilde{\theta}_e)\frac{\partial\tilde{\theta}_e}{\partial r}.$$

The effect of changes in r on the value of the incumbent is

$$\frac{\partial \tilde{V}_i}{\partial r} = \frac{\tilde{V}_i}{r} - \pi \frac{\partial \tilde{\theta}_e}{\partial r} + r\tilde{\theta}_i f''(\tilde{\theta}_i)\frac{\partial \tilde{\theta}_i}{\partial r}.$$

For ($\phi < 1$) the last two terms in the expression are negative. Substituting explicitly for $\tilde{V}_i$, $\partial\tilde{\theta}_e/\partial r$ and $\partial\tilde{\theta}_i/\partial r$ we have

$$\frac{\partial \tilde{V}_i}{\partial r} = -f'(\tilde{\theta}_i) - \frac{\pi\,[\tilde{\pi} - b]}{|J|} f'(\tilde{\theta}_i)(1-\tilde{\theta}_i)(1-\phi). \tag{A2}$$

The results for changes in ($\tilde{\pi}$) follow from the derivatives:

$$\frac{\partial \tilde{\theta}_e}{\partial \tilde{\pi}} = \frac{\phi[\tilde{\pi} - (1-\tilde{\theta}_e)\pi] - [\tilde{\pi} - b]}{|J|} \qquad \textit{and} \qquad \frac{\partial \tilde{V}_e}{\partial \tilde{\pi}} = r\tilde{\theta}_e f''(\tilde{\theta}_e)\frac{\partial \tilde{\theta}_e}{\partial \tilde{\pi}}.$$

To sign $\partial\tilde{\theta}_e/\partial\tilde{\pi}$, substitute for $[\tilde{\pi} - b]$ using A1 The numerator of the derivative is then

$$rf'(\tilde{\theta}_i)\left\{\phi - f'(\tilde{\theta}_e)\left(\frac{\tilde{\pi} - (1-\tilde{\theta}_e)\pi}{r}\right)^{\frac{1-\phi}{\phi}}\right\} \tag{A3}$$

So long as the incumbent is active, we know that $\tilde{\pi} - (1-\tilde{\theta}_e)\pi \geq r$. The smallest value that $f'(\tilde{\theta}_e)$ can take is 1, and only if the entrant was passive. Thus for $\phi \leq 1$, we can be sure the entrant's R&D is decreasing in $\tilde{\pi}$. This, in turn, permits us to sign $\partial\tilde{V}_e/\partial\tilde{\pi}$.

The effect of increases in $\tilde{\pi}$ on the incumbent's market value is

$$\frac{\partial \tilde{V}_i}{\partial \tilde{\pi}} = r\tilde{\theta}_i f''(\tilde{\theta}_i)\frac{\partial \tilde{\theta}_i}{\partial \tilde{\pi}} - \pi\frac{\partial \tilde{\theta}_e}{\partial \tilde{\pi}}.$$

We know from Proposition (4) the first terms is positive The second terms is also positive when $\phi \leq 1$.

Part (c) of the proposition again follow from the fact that $\tilde{\pi} - (1-\tilde{\theta}_e)\pi \geq r$ in the interior equilibrium. Note this is a sufficient condition. The constraint implied by (A3) can be also be solved numerically We omit this constraint in Figure 4, since it is redundant to the constraint required to sign $\partial\tilde{V}_i/\partial\tilde{\pi}$ (which is constructed in the next proof). ■

Proposition 6

Proof. When $\phi > 1, \partial\tilde{V}_i/\partial r$ cannot be explicitly signed. Rearranging terms, the sign of this derivative is the sign of $(\phi - 1)^2\pi[\tilde{\pi} - b] - [1 - (1 - \tilde{\theta}_i)^{\phi-1}]\,|J|$, the expression contained in part (a) of the proposition. This solved numerically and plotted as the red line in Figure 4. Note that as we take the limit as $\tilde{\theta}_i \to 0$, the expression is positive (increasing r increases the value of the incumbent). Conversely, if we take the limit as negative $\tilde{\theta}_i \to 1$, the expression is negative.

The effect of changes in ϕ on the incumbent's market value is follows from the derivative:

$$\frac{\partial \tilde{V}_i}{\partial \phi} = r\tilde{\theta}_i f''(\tilde{\theta}_i)\frac{\partial \tilde{\theta}_i}{\partial \phi} - \pi \frac{\partial \tilde{\theta}_e}{\partial \phi}.$$

From Proposition (4), we know the sign of the first part of the expression is negative. In general, however, the derivative $\partial\tilde{\theta}_e/\partial\phi$ cannot be signed. Substituting for $\partial\tilde{\theta}_i/\partial\phi$ and $\partial\tilde{\theta}_e/\partial\phi$, and rearranging terms, $\partial\tilde{V}_i/\partial\phi$ takes the sign of the following expression

$$\tilde{\theta}_i\,|J|\ln(1-\tilde{\theta}_i) + (1-\tilde{\theta}_i)\pi[\tilde{\pi} - b]\left\{\ln(1-\tilde{\theta}_i) - \phi\ln(1-\tilde{\theta}_e)\right\}.$$

This is the condition specified in part (b) of the Proposition. Note that the expression in brackets takes the opposite sign of $\partial\tilde{\theta}_e/\partial\phi$. This constraint is solved numerically and plotted as the brown line in Figure 4. Note that if the incumbent is relatively passive $\partial\tilde{V}_i/\partial\phi > 0$. In this case, greater curvature of the cost function reduces the entrant's R&D intensity, which increases the value of the incumbent. On the other hand, if the incumbent is very active in R&D increases in the curvature of the R&D cost function reduces the incumbent's R&D intensity while, on net, increasing the R&D intensity of the entrant. In that case, the value of the incumbent falls.

Changes in $\tilde{\pi}$ affect the value of the incumbent according to the following derivative:

$$\frac{\partial \tilde{V}_i}{\partial \tilde{\pi}} = r\tilde{\theta}_i f''(\tilde{\theta}_i)\frac{\partial \tilde{\theta}_i}{\partial \tilde{\pi}} - \pi \frac{\partial \tilde{\theta}_e}{\partial \tilde{\pi}}.$$

From Proposition (4), we know the sign of the first part of the expression is positive. When $\phi \leq 1$, we know $\partial\tilde{\theta}_e/\partial\tilde{\pi} < 0$ and we know that $\tilde{V}_i$ is increasing in $\tilde{\pi}$. For values of $1 < \phi < [\tilde{\pi} - b]/r$, we have to verify the sign of $\partial\tilde{\theta}_e/\partial\tilde{\pi}$, as described in the preceding proof. For values of $\phi > [\tilde{\pi} - b]/r$, we know $\partial\tilde{\theta}_e/\partial\tilde{\pi} > 0$, and the sign of $\partial\tilde{V}_i/\partial\tilde{\pi}$ is ambiguous. Substituting for $\partial\tilde{\theta}_i/\partial\tilde{\pi}$ and $\partial\tilde{\theta}_e/\partial\tilde{\pi}$, and rearranging terms, $\partial\tilde{V}_i/\partial\tilde{\pi}$ takes the sign of the following expression:

$$\pi[\tilde{\pi} - b] + \tilde{\theta}_i r^2 f''(\tilde{\theta}_i) f''(\tilde{\theta}_e) - \pi r\phi(1-\tilde{\theta}_i)^{1-\phi}.$$

This is the condition specified in part (c) of the proposition. We solve this constraint numerically and plot it as the blue line in Figure 4. Note that almost everywhere the constraint in Proposition (6a) is satisfied, this constraint is also satisfied. The exception is where $\tilde{\theta}_e \to 0$, near the entrant's participation constraint. ■

6.2. 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 7 $\theta_2^e\leq\theta_1^e$ *but* $(1-\theta_2^e)^2\leq(1-\theta_1^e)$.

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

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

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 8 $\theta_2^i\leq\theta_1^i$.

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 9 $V_1^j > V_2^j$ *and* $V_2^i > V_1^i$.

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

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

The result then follows from the previous lemmas. ■

Corollary 10 *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

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

and

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

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

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

Lemma 11 $\frac{\partial \theta_2^e}{\partial b} \leq 0$.

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

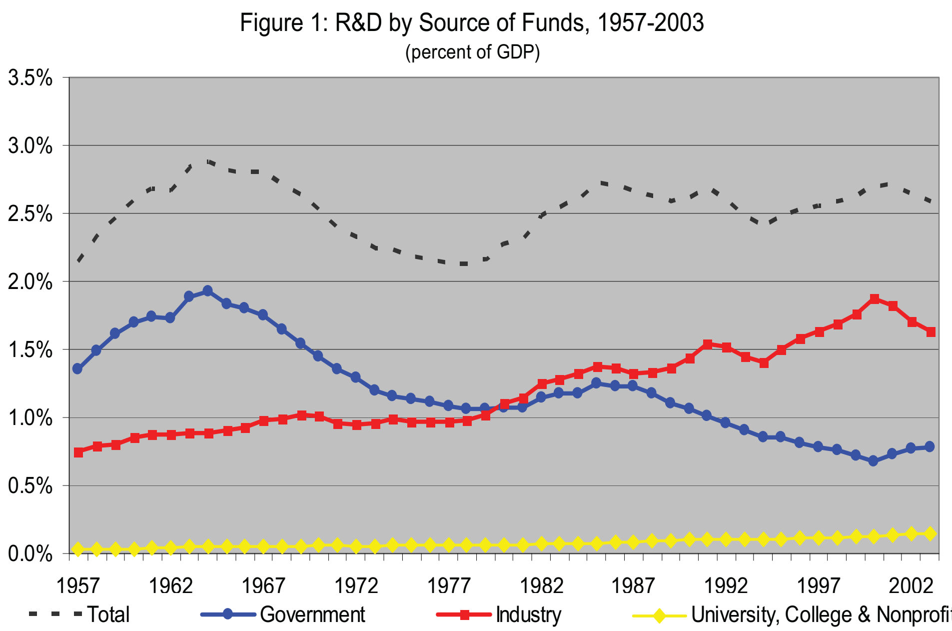
$$\frac{b\pi}{\tilde{\pi}^2}\left(\frac{\theta_2^e}{1-\theta_2^e}\right)^2 - \frac{1}{2}.$$

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

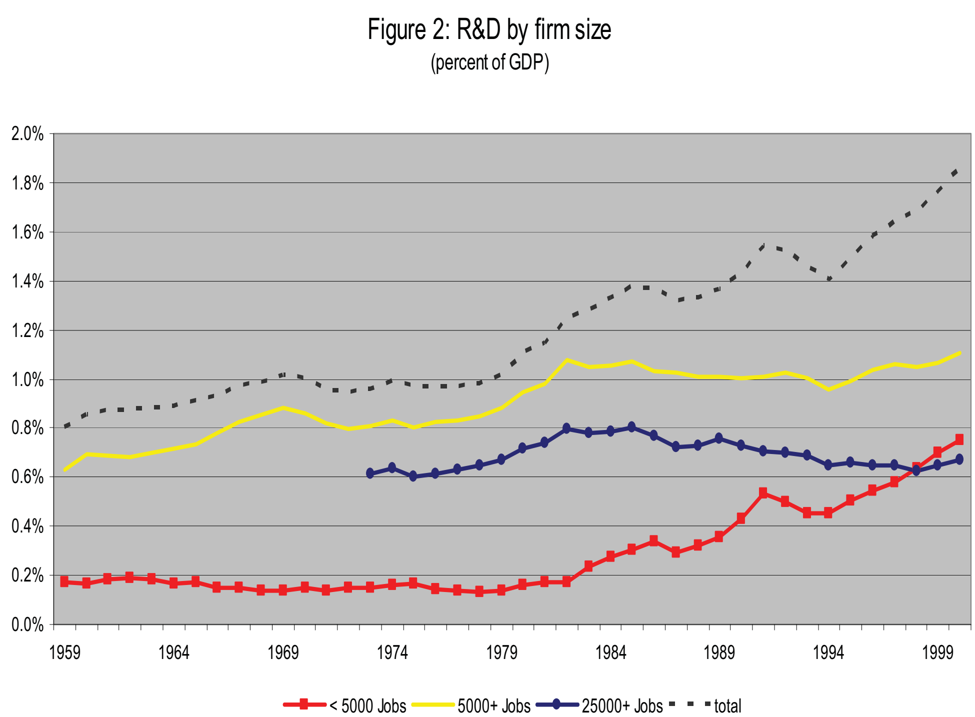
$$(1-\alpha)\left(\frac{1+\alpha-\sqrt{1+\alpha^2(2-\alpha)}}{(1-\alpha)^2+\sqrt{1+\alpha^2(2-\alpha)}}\right)^2.$$

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

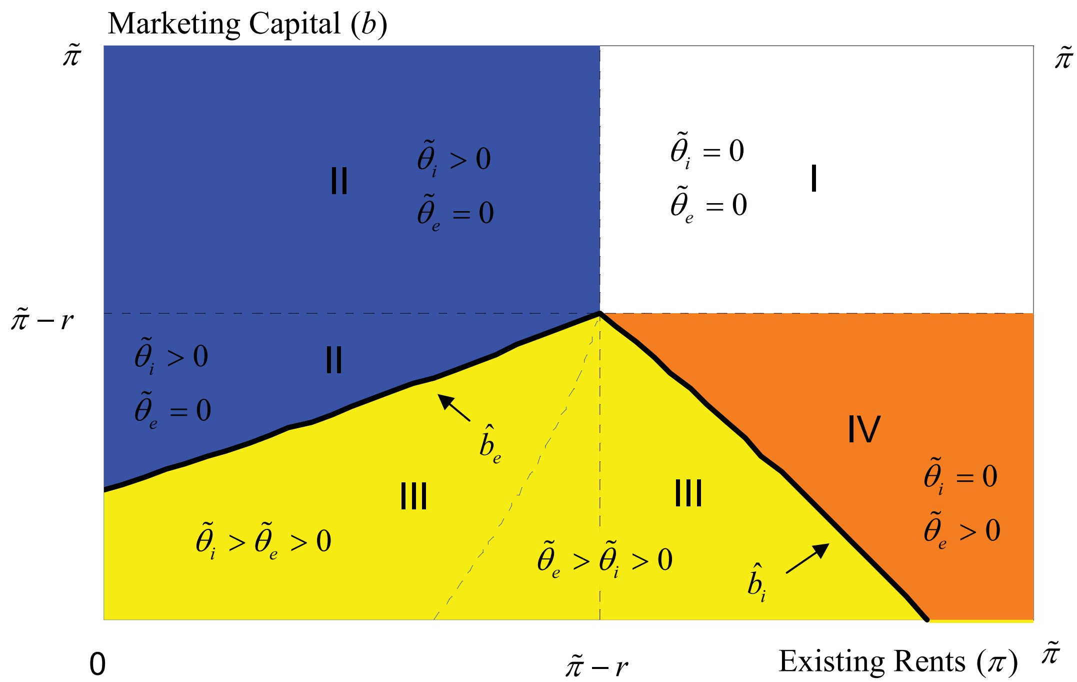


Source: National Science Foundation and authors' calculations



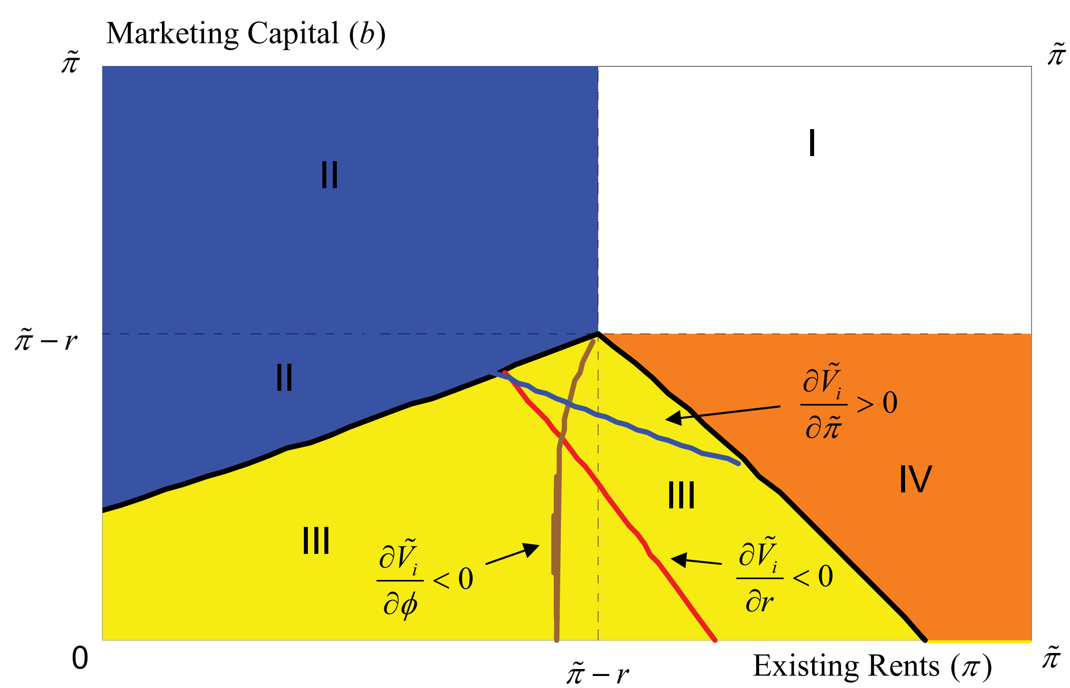
Source: National Science Foundation and authors' calculations

Figure 3: Participation Constraints in (b,π) space



parameters: $\tilde{\pi} = 1.5,\ r = 0.7,\ \phi = 1.5$

Figure 4: Identification Constraints in (b,π) space



parameters: $\tilde{\pi} = 1.5,\ r = 0.7,\ \phi = 1.5$

Figure 5: Investment in R&D, Computers, & Software
(Percent of GDP)

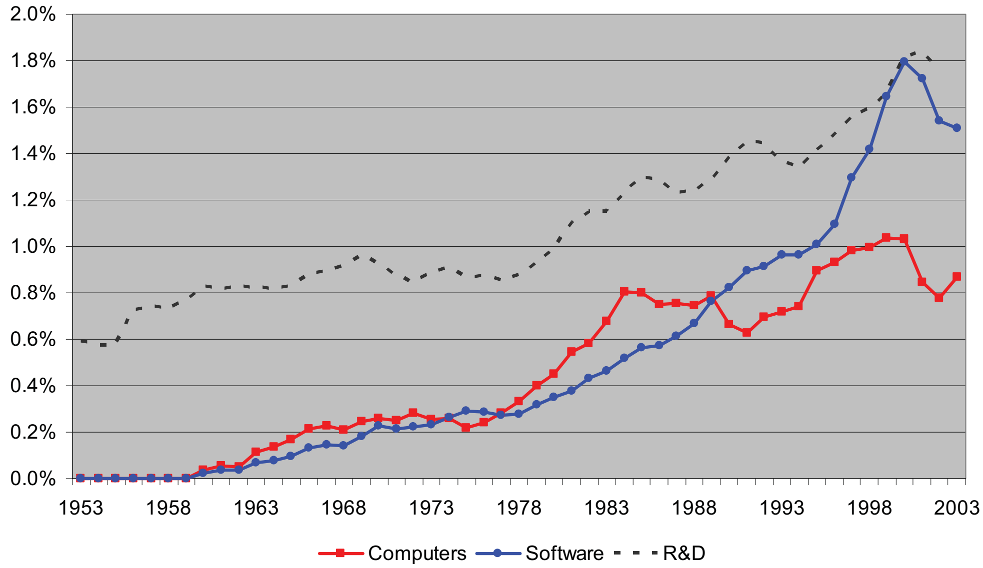


Table 1: Testable Implications of the Duopoly Model*					
	Changes in Exogenous Parameters				
	↓ Price of Marketing Capital (b)	↑ Existing Rents (π)	↑ Invention Size ($\tilde{\pi}$)	↓ Price of R&D (r)	↑ Curvature of R&D Cost Fct. (ϕ)
R&D Reaction Function (for all values of ϕ)					
Incumbent	∅ ¢	↓	↑	↑	↓
Entrant	↑	∅	↑	↑	↓
($\phi \leq 1$)					
R&D					
Incumbent	↑	↓	↑	↑	↓
Entrant	↑	↑	↓	↓ †	?
Ex Ante Firm Value					
Incumbent	↓	↑	↑	↑	↓ #
Entrant	↑	↑	↓	↓	?
($\phi > 1$)					
R&D					
Incumbent	↑	↓	↑	↑	↓
Entrant	↑	↑	?	↑	?
Ex Ante Firm Value					
Incumbent	↓	↑	↑ §	↑ $	↓ #
Entrant	↑	↑	?	?	?

*: For results allowing for entry by more than one firm, see section 2.2.1 and the Appendix. ¢: Increasing if the incumbent must sink γb, where $\gamma \in (0,1)$. †: There is no change if $\phi = 1$. $: Assumes the condition specified in Proposition 6 (a) is satisfied. #: Assumes the condition specified in Proposition 6 (b) is satisfied. §: Assumes the condition specified in Proposition 6 (c) is satisfied.

Table 2: Industries with Aggregate R&D Intensity of 1% or More in 1973 (R&D Industries)

SIC	Industry Description	SIC	Industry Description
280	Chemicals & Allied Products	362	Electrical Industrial Apparatus
281	Industrial Inorganic Chemicals	363	Household Appliances
282	Plastics Materials & Synthetic Resins	365	Household Audio & Video Equipment
283	Drugs	3661	Telephone & Telegraph Apparatus
2834	Pharmaceutical Preparations	3663	Radio & Television Broadcasting & Communications Equipment
284	Soap, Detergents, & Cleaning Preparations	367	Electronic Components & Accessories
2844	Perfumes, Cosmetics, & Other Toilet Preparations	3674	Semiconductors & Related Devices
2851	Paints, Varnishes, Lacquers, Enamels, & Allied	3678	Electronic Connectors
286	Industrial Organic Chemicals	3711	Motor Vehicles & Passenger Car Bodies
289	Miscellaneous Chemical Products	3713	Truck & Bus Bodies
301	Tires & Inner Tubes	3714	Motor Vehicle Parts & Accessories
322	Glass & Glassware, Pressed Or Blown	372	Aircraft & Parts
329	Abrasive, Asbestos, & Miscellaneous	3721	Aircraft
3334	Primary Production of Aluminum	3724	Aircraft Engines & Engine Parts
342	Cutlery, Hand Tools, & General Hardware	376	Guided Missiles & Space Vehicles & Parts
348	Ordnance & Accessories, Except Vehicles	381	Search, Detection, Navigation, Guidance
351	Engines & Turbines	382	Laboratory Apparatus & Analytical, Optical, Measuring, & Control Instruments
352	Farm & Garden Machinery & Equipment	3822	Automatic Controls for Regulating Residential & Commercial Environments & Appliances
353	Construction, Mining, & Materials Handling	3823	Industrial Instruments for Measurement, Display, & Control of Process Variables; & Related Products
3531	Construction Machinery & Equipment	3825	Instruments for Measuring & Testing of Electricity & Electrical Signals
3533	Oil & Gas Field Machinery & Equipment	3826	Laboratory Analytical Instruments
3537	Industrial Trucks, Tractors, Trailers, & Stackers	384	Surgical, Medical, & Dental Instruments
354	Metalworking Machinery & Equipment	3841	Surgical & Medical Instruments & Apparatus
3541	Machine Tools, Metal Cutting Types	3842	Orthopedic, Prosthetic, & Surgical Appliances & Supplies
355	Special Industry Machinery, Except Metalworking	3843	Dental Equipment & Supplies
3555	Printing Trades Machinery & Equipment	3861	Photographic Equipment & Supplies
356	General Industrial Machinery & Equipment	394	Dolls, Toys, Games & Sporting & Athletic Goods
3561	Pumps & Pumping Equipment	504	Professional & Commercial Equipment & Supply - Wholesale
357	Computer & Office Equipment	7372	Prepackaged Software
3571	Electronic Computers	7373	Computer Integrated Systems Design
3572	Computer Storage Devices	7374	Computer Processing & Data Processing Services
3575	Computer Terminals	807	Medical & Dental Laboratories
3585	Air-Conditioning, Warm Air Heating, & Commercial & Industrial Refrigeration Equipment	873	Research, Development, & Testing Services
360	Electronic & Other Electrical Equipment & Components, Except Computer Equipment	Misc	Misc. Metal Ores, Oil & Coal Products, Primary Metal Products; Watches, Clocks, Clockwork Devices; Musical Instruments; Cogeneration
361	Electric Transmission & Distribution Equipment		

Table 3: 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 4: 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 5: 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 6: Descriptive Statistics (R&D Industries, 1973-97)						
	All Firms	Computers	Non-computer Industries			
			Incumbent Industries			Non-incumbent Industries
Variable:			All Firms	Incumbent Firms	Other Firms	
	Compustat Variables					
Employment (1,000s)	6.78 6.74	3.60 4.52	16.38 11.38	93.36 31.18	5.38 3.02	2.09 1.59
Operating Costs ($ mil.)	906 1,292	442 1,138	2,259 2,075	13,594 5,704	668 587	263 267
R&D†	0.0595 0.0306	0.0922 0.0393	0.0374 0.0251	0.0362 0.0147	0.0375 0.0263	0.0537 0.0274
Rival's R&D†	0.0609 0.0141	0.0927 0.0153	0.0407 0.0109	0.0345 0.0113	0.0415 0.0109	0.0544 0.0153
Book Net Worth†	0.5797 0.2618	0.6294 0.2738	0.4971 0.2230	0.3805 0.1143	0.5135 0.2343	0.6053 0.2785
Market Value†	1.4955 1.2015	1.8369 1.3595	1.1359 1.0159	0.6719 0.5204	1.2011 1.0672	1.5256 1.2122
Rival's Mkt. Val†.	1.4703 0.672	2.0495 0.7586	0.9878 0.4882	0.7150 0.4477	1.0261 0.4936	1.4326 0.7214
Share of R&D, 1973	100.0%	25.5%	74.5%	65.0%	47.4%	17.6%
	Other Variables					
*PC Computer use, 1984**	41.94% 18.16	65.38% 17.95	37.5% 10.98	37.17% 12.04	37.54% 10.82	34.29% 12.35
*Concentration Ratio**	49.57% 18.93	43.45% 21.44	61.29% 16.67	71.65% 20.39	59.91% 15.60	44.78% 14.21
	Data set restricted to firms matched to NBER Patent Citations Data File					
Patents†	0.1220 0.2218	0.1027 0.1044	0.0919 0.1843	0.0699 0.0283	0.0968 0.2034	0.1604 0.2871
Rival's Patents†	0.0721 0.0279	0.0817 0.0350	0.0606 0.0193	0.0582 0.0237	0.0612 0.0182	0.0785 0.0308
Share of R&D, 1973	100.0%	22.7%	77.3%	68.7%	50.8%	18.0%

Notes: Each cell includes the mean, followed by the *within* standard deviation (the total standard deviation is reported for variables marked with a *). Statistics exclude observations where market value (divided by operating expenses) is ≥ 14, or net worth (divided by operating expenses) ≥ 4 or ≤ -0.1. †: Variables normalized by own, or the sum of rivals' operating expenses. All financial variables in levels are deflated using the GDP deflator (2000 = 100).

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 at some point in time. The rival variables are calculated by taking the sum of the variable over all other firms in the industry.

Employees, R&D, and book net worth are Compustat variables data29, data46, and data216, respectively. Operating costs are the sum of costs of goods sold (data41) and selling, general, and administrative expenses (data189). Market value is the product of the firm's end of year closing price (data24) and common shares outstanding (data25). PC computer use is the share of full time workers in an industry indicating they use a PC at work in the March 1984 supplement to the Current Population Survey. Concentration ratio is the share of shipments (receipts) of the 8 largest firms in manufacturing, wholesaling, retailing, or services industries as reported in the Census of Industry every 5 years (between years are interpolated). Patents is the sum of the firm's patents over the previous 5 years, as reported in the NBER Patent Citations Data File, divided by operating expenses in the previous year.

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

Dependent Variable: $R\ \&\ D^{i}_{j,t}$	All Firms	Computers	Non-computer Industries			
			Incumbent Industries			Non-incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
Constant	0.0546*** (0.0015)	0.0818*** (0.0055)	0.0219*** (0.0018)	0.0236*** (0.0024)	0.0221*** (0.0021)	0.0556*** (0.002)
$R\ \&\ D^{\sim i}_{j,t-1}$	-0.2157*** (0.0331)	-0.1284 (0.0878)	0.0678 (0.0554)	0.0283 (0.0818)	0.0587 (0.0627)	-0.3107*** (0.0477)
$comp_{t-1} \cdot R\ \&\ D^{\sim i}_{j,t-1}$	0.4329*** (0.0355)	0.4251*** (0.0963)	0.5503*** (0.0581)	0.8288*** (0.0918)	0.5383*** (0.0653)	0.3361*** (0.0527)
Firms	4,153	1,387	969	59	910	1,797
Observations	34,504	9,455	10,413	1,307	9,106	14,636
Within R^2	0.0273	0.0281	0.1010	0.3867	0.0876	0.0186

Notes: Standard errors are in parentheses. * significant at 10 percent. ** significant at 5 percent. *** significant at 1 percent. Regressions exclude observations where market value (divided by operating expenses) is ≥ 14, or net worth (divided by operating expenses) ≥ 4 or ≤ -0.1. $comp_{t-1}$ is nominal investment in computers divided by nominal GDP. For other variable definitions, the notes to Table 6 and the text.

Table 8: Reaction Function Regressions with Additional Controls, Fixed and Year Effects (R&D Industries ex Computers, 1973-97)

Dependent Variable: $R\&D^{i}_{j,t}$	Incumbent Industries		Non-incumbent Industries	Incumbent Industries		Non-incumbent Industries	Incumbent Industries		Non-incumbent Industries
	Incumbents	Other		Incumbents	Other		Incumbents	Other	
Constant	0.0318*** (0.0026)	0.0283*** (0.0027)	0.0473*** (0.0024)	0.0236*** (0.0036)	0.0267*** (0.0031)	0.0631*** (0.0028)	0.0071 (0.008)	0.0271*** (0.0053)	0.0621*** (0.0046)
$R\&D^{\sim i}_{j,t-1}$	-0.2416*** (0.0849)	-0.0639 (0.0703)	-0.1645*** (0.0513)	0.2512** (0.1152)	0.1324 (0.0863)	-0.3990*** (0.0622)	0.3625*** (0.1073)	0.1146 (0.0771)	-0.2776*** (0.0695)
$comp_{t-1} \cdot R\&D^{\sim i}_{j,t-1}$	0.7781*** (0.099)	0.4279*** (0.0709)	0.3326*** (0.0538)	0.6490*** (0.1096)	0.5429*** (0.0803)	0.4480*** (0.0609)	0.7733*** (0.093)	0.5734*** (0.0659)	0.3012*** (0.0708)
$MV^{i}_{j,t-1}$	-0.0021 (0.0018)	0.0013*** (0.0003)	0.0016*** (0.0002)						
$MV^{i}_{j,t-1} \cdot R\&D^{\sim i}_{j,t-1}$	0.106*** (0.0258)	0.002 (0.0037)	-0.0052* (0.0028)						
$MV^{\sim i}_{j,t-1}$	-0.0028* (0.0017)	-0.0062*** (0.0014)	0.001 (0.0008)						
$MV^{\sim i}_{j,t-1} \cdot R\&D^{\sim i}_{j,t-1}$	0.0129 (0.0265)	0.0767*** (0.0129)	-0.0306*** (0.0061)						
$Pat^{i}_{j,t-1}$				0.0016 (0.0241)	0.0206*** (0.0033)	0.0059*** (0.0022)			
$Pat^{i}_{j,t-1} \cdot R\&D^{\sim i}_{j,t-1}$				-0.1353 (0.522)	0.0188 (0.0497)	-0.1285*** (0.0376)			
$Pat^{\sim i}_{j,t-1}$				-0.0112 (0.0281)	-0.1064*** (0.0347)	-0.1172*** (0.0198)			
$Pat^{\sim i}_{j,t-1} \cdot R\&D^{\sim i}_{j,t-1}$				-0.7072 (0.5607)	0.1368 (0.5469)	1.3693*** (0.2566)			
$CR8_{j,t-1}$							0.0002* (0.0001)	-0.0001 (0.0001)	-0.0002** (0.0001)
$CR8_{j,t-1} \cdot R\&D^{\sim i}_{j,t-1}$							-0.0034*** (0.0009)	-0.0015 (0.001)	0.0008 (0.0005)
Firms	58	872	1,698	54	364	514	53	844	1,608
Observations	1,304	8,650	13,628	1,218	5,413	6,902	1,079	7,873	11,526
Within R^2	0.4427	0.1091	0.0318	0.4034	0.1771	0.0555	0.4338	0.0971	0.0155

Notes: Standard errors are in parentheses. * significant at 10 percent. ** significant at 5 percent. *** significant at 1 percent. $comp_{t-1}$ is nominal investment in computers divided by nominal GDP. For other variable definitions, see notes to Table 6 and the text.

Table 9: Reaction Function Regressions with Fixed and Year Effects (R&D Industries, 1973-97)						
	Early PC Adopters					
Dependent Variable: $R\&D^{i}_{j,t}$	All Firms	Computers	Non-computer Industries			
			Incumbent Industries			Non-incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
Constant	0.0742*** (0.0032)	0.089*** (0.0078)	0.0263*** (0.0037)	0.0234*** (0.0041)	0.0265*** (0.0043)	0.0916*** (0.0059)
$R\&D^{\sim i}_{j,t-1}$	-0.1968*** (0.0565)	-0.1140 (0.1169)	0.1119 (0.0855)	-0.0090 (0.1141)	0.1278 (0.0972)	-0.2357** (0.1016)
$comp_{t-1} \cdot R\&D^{\sim i}_{j,t-1}$	0.4115*** (0.066)	0.426*** (0.1283)	0.5272*** (0.0955)	1.164*** (0.1321)	0.4701*** (0.1089)	0.1865 (0.1339)
Firms	2,100	1,077	450	21	429	573
Observations	15,889	6,594	4,751	507	4,244	4,544
Within R^2	0.0303	0.0244	0.1287	0.5127	0.1168	0.0256
	Late PC Adopters					
Constant	0.0307*** (0.0015)	—	0.0232*** (0.002)	0.0239*** (0.0031)	0.0256*** (0.0023)	0.035*** (0.002)
$R\&D^{\sim i}_{j,t-1}$	-0.1156** (0.0581)	—	-0.1784* (0.0942)	0.1671 (0.1361)	-0.3118*** (0.1147)	-0.1438* (0.0739)
$comp_{t-1} \cdot R\&D^{\sim i}_{j,t-1}$	0.2254*** (0.0607)	—	0.4725*** (0.1094)	0.1690 (0.1506)	0.4807*** (0.1355)	0.2194*** (0.076)
Firms	1,690	0	466	38	428	1,224
Observations	15,325	0	5,233	800	4,433	10,092
Within R^2	0.0167	—	0.028	0.2582	0.0173	0.0175

Notes: Standard errors are in parentheses. * significant at 10 percent. ** significant at 5 percent. *** significant at 1 percent. Regressions exclude observations where market value (divided by operating expenses) is ≥ 14, or net worth (divided by operating expenses) ≥ 4 or ≤ -0.1. $comp_{t-1}$ is nominal investment in computers divided by nominal GDP. For other variable definitions, the notes to Table 6 and the text.

Table 10: Market Value Regressions with Fixed Firm and Industry Year Effects (& Heckman Correction) (R&D Industries, 1973-97)

Dependent Variable: $MV^i_{j,t}$	All Firms	Computer Industries	Non-computer industries			
			Incumbent Industries			Non-incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
constant	-0.0445*** (0.0109)	-0.1648*** (0.0364)	-0.0003 (0.0139)	-0.0132 (0.01)	-0.0001 (0.0185)	-0.037** (0.0166)
$comp_{t-1}$	0.9104 (1.6257)	0.8381 (1.4354)	1.0055 (0.8581)	-6.4378*** (0.637)	0.3432 (2.2911)	0.7012 (1.625)
BV^i_{t-1}	1.3526*** (0.098)	1.7436*** (0.2436)	1.0321*** (0.1469)	0.3183 (0.2645)	0.9756*** (0.1701)	1.4228*** (0.1513)
$comp_{t-1} \cdot BV^i_{t-1}$	-0.6655*** (0.139)	-1.237*** (0.3505)	-0.3713* (0.2017)	0.0066 (0.4053)	-0.248 (0.2328)	-0.6309*** (0.2171)
$R\&D^{\sim i}_{j,t-1}$	6.4877*** (0.8329)	13.9511*** (1.7412)	2.9912** (1.265)	1.3991 (1.9305)	3.7008** (1.467)	0.6673 (1.4359)
$comp_{t-1} \cdot R\&D^{\sim i}_{j,t-1}$	-5.1423*** (1.1341)	-16.7397*** (2.3276)	2.6802 (1.7837)	10.3986*** (2.6266)	1.1735 (2.0915)	1.085 (1.9351)
$Pat^i_{j,t-1}$	0.0455 (0.0507)	0.6417* (0.3788)	-0.174 (0.1182)	4.7298*** (0.8207)	-0.0998 (0.131)	0.0859 (0.0559)
$comp_{t-1} \cdot Pat^i_{j,t-1}$	0.1437 (0.1185)	-0.8308 (0.6783)	0.84*** (0.2715)	-4.6268*** (1.2563)	0.7458** (0.3009)	-0.0498 (0.1348)
n, 2nd stage	15,042	3,113	5,759	1,211	4,548	6,170
n, 1st stage	27,756	8,049	8,302	1,266	7,036	11,405
Wald Statistic	1,647.20	1,101.55	950.13	894.97	690.72	622.74

Notes: Standard errors are in parentheses. * significant at 10 percent. ** significant at 5 percent. *** significant at 1 percent. Regressions exclude observations where market value (divided by operating expenses) is ≥ 14, or net worth (divided by operating expenses) ≥ 4 or ≤ -0.1. Regressions are run on de-meaned variables, with a selection correction for firms matched to their patents in the NBER Patent Citations Data File. Explanatory variables in the first stage regression include real R&D and assets (in logs), a dummy for young firms (1st 5 years in Compustat) and year dummies. $comp_{t-1}$ is nominal investment in computers divided by nominal GDP. BV^i_{t-1} is the book value of equity and retained earnings (e.g. net worth), divided by operating expenses. For other variable definitions, the notes to Table 6 and the text.

Table 11: Marginal Effects (1995) of an increase in Computer Investment/GDP						
Dependent Variable: $MV_{j,t}^{i}$	All Firms	Computer Industries	Non-computer industries			
			Incumbent Industries			Non-incumbent Industries
			All Firms	Incumbent Firms	Other Firms	
$comp_{t-1}$	—	—	—	-4.68	—	—
$comp_{t-1} \cdot BV_{t-1}^{i}$	-0.06	-0.16	-0.04	0.00	—	-0.07
$comp_{t-1} \cdot R\&D_{j,t-1}^{\sim i}$	-0.02	-0.12	0.00	0.26	—	—
$comp_{t-1} \cdot Pat_{j,t-1}^{i}$	—	—	0.02	-0.18	0.04	—
total	-0.09	-0.28	-0.02	-4.60	0.04	-0.07
Change in Mkt Value ($ billions)*	-1.9	-1.4	-0.3	-31.9	0.2	-0.2

Notes: The coefficients are calculated as elasticities. Based on regressions reported in Table 10 and the means of the right hand side variables in 1995. Insignificant coefficients are set to zero. $comp_{t-1}$ is nominal investment in computers divided by nominal GDP. For other variable definitions, the notes to Table 6 and the text. *: change in 1995 market value induced by a 1% increase in the ratio of computer investment to GDP.