A Test of the Optimality of R&D Allocation

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Abstract

This paper statistically tests the optimality of rule-of-thumb allocation of R&D funding. Models of firms with market power are compared with a model of perfectly competitive firms. It is shown that competitive firms optimally spend a fixed fraction of total revenue on R&D. Conditions generating this rule of thumb for the competitive firm are more general than those generating similar results for firms with market power. This suggests a statistical test of the optimality of rule-of-thumb R&D expenditures. Two versions of the test support the predictive capability of profit-maximizing models of R&D allocation.

Introduction

It has been noted often that firms allocate a fixed percentage of total revenue to research and development (R&D) over time.[1] Various models involving firms with market power have shown that this fixed percentage rule (or rule of thumb) may be profit maximizing if demand functions are log linear (e.g., Grabowski, 1970; Nakao, 1982; and Nerlove and Arrow, 1962). An alternative explanation, not limited to industries with log-linear demand functions, is that the rule of thumb is a satisficing response to uncertainty (e.g., Hay and Morris, 1979; Mansfield, 1968). Statistical tests performed with the ratio of R&D expenditures to sales can support either of the two explanations, because both explanations result in observationally equivalent behavior. From the profit-maximizing

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[1]Firms' actual use of a fixed percentage rule is mentioned in Grabowski (1970), Hay and Morris (1979), Mansfield (1968), and Nerlove and Arrow (1962). The rule is supported empirically (but without theoretical underpinning) by Bullard and Straka (1986) for the paper industry and by Link, Seaks, and Woodbery (1988) for nine separate industry groupings.

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perspective, fluctuations around a firm's average ratio of R&D to total revenue can be attributed to demand curves that are not log linear; from the satisficing perspective, fluctuations can be rationalized as a response to short-run opportunities (Hay and Morris, 1979, p. 446).

Because previous profit-maximizing models of R&D involve firms with market power, an alternative approach to testing the optimality of R&D allocation is to discern differences in R&D behavior between firms with market power and competitive firms. This research models R&D allocation by a profit-maximizing competitive firm and finds that the optimal R&D/sales ratio is constant regardless of the functional form of demand. This is because the optimal R&D/sales ratio is, in part, a function of the equilibrium price and a limit on the available technology, both of which are beyond the control of the competitive firm. In contrast, firms with market power have more control over price and the technology limit, so the optimal R&D/sales need not be constant. Because a noncompetitive firm's optimal R&D/sales is a function of demand elasticities, the ratio will be constant only if the elasticities are constant or, equivalently, if the demand function is log linear (e.g., Nakao, 1982; Nerlove and Arrow; 1962).These models suggest that the variability of R&D/sales is related directly to market power if firms fund R&D in a profit-maximizing manner. In contrast, the satisficing hypothesis suggests no relationship between market power and the variability of the R&D/sales ratio because it suggests that any firm will engage in rule-of-thumb behavior regardless of market structure. Statistical tests confirm a positive relationship between R&D/sales variability and market power. This, in turn, supports the rule of thumb as profit-maximizing behavior.

R&D in a Competitive Industry

Because Schumpeter (1962) emphasized monopolistic and oligopolistic industries, little attention has been given to R&D in competitive industries. But competitive firms often engage in R&D. For instance, in agriculture (generally regarded as highly competitive), Evenson (1982, pp. 237-241) reported that family farmers often engage in R&D.

If a competitive firm could use R&D to differentiate its product and thus gain market power, then the incentive for R&D would be obvious. Similarly, a competitive firm may have an incentive to engage in R&D if the firm could increase the minimum efficient scale (MES), which would reduce the equilibrium number of firms in the market and possibly increase remaining firms' market power. This paper considers, instead, the case where the market is, and will remain, competitive and develops a model in which a competitive firm engages in cost-reducing (but not necessarily MES-increasing) R&D in order to remain in the market. Such behavior often is observed (e.g., in the forestry, agricultural, and textile and apparel industries).

Consider a competitive industry in which firms produce a homogeneous good. Suppose firms perceive investment in (cost-reducing) R&D to be necessary to remain in the market. Following analyses of advertising in a competitive industry (e.g., Gould, 1970; Telser, 1964), R&D expenditures are treated as additional costs. Any firm would benefit from being the only one to apply the results of R&D because the firm could gain a temporary cost advantage. Thus, each firm faces a prisoner's dilemma, and each engages in R&D.[2] Economic profit in any period is total revenue net of production and R&D costs. In long-run equilibrium, economic profit equals zero.

External agent involvement in basic R&D is common in relatively competitive industries because basic R&D is a high risk proposition for firms with no guarantee of usable results. For example, government may perform basic R&D and make the findings freely available.[3] Then firms engage in applied R&D to implement the government's results. Because the feasibility of the new technology has been demonstrated, there is little uncertainty concerning results; it merely remains for the firms to perform the applied R&D necessary to incorporate the knowledge into their production process.[4]

In this study, a competitive firm engages in applied R&D after the feasibility of the new methods has been demonstrated. The invisible hand of competition offers both a carrot and a stick to compel a competitive firm to engage in applied R&D. The carrot is the potential, albeit fleeting, profit to be gained from being the first to achieve lower costs by employing new techniques made possible by the basic R&D. The stick is the possibility that if a firm is too slow to employ the R&D, the other firms will achieve lower costs and sell

[2]Clearly, an equilibrium in which these firms engage in R&D is a Nash equilibrium: when all firms engage in R&D, no single firm unilaterally could improve its position by ceasing research activity because it would be forced from the market.

[3]Much government R&D for agriculture and textiles and apparel is conducted at state agricultural experiment stations (often associated with land grant universities), schools of home economics, and departments of textiles and fabrics. The information is disseminated through the USDA extension services. The USDA supports research in forestry and wood products at regional forest experiment stations and at the USDA Forest Products Laboratory in Madison, Wisconsin.

[4]There are many cases where a firm outside the industry obtains a patent on a new process and leases the patent to firms within the industry. This case is analyzed by Arrow (1962).

the good at a lower price. The laggard would incur at least temporary losses and could be forced from the market.

The Firm and the Industry: Assumptions

Suppose the supplies of labor (L) and other inputs (K) are perfectly elastic at prices w and r. The industry faces the inverse demand curve

$$p(t) = p\,(Q(t))$$

where:

p(t) = price; and
Q(t) = industry output at time t.

Each firm takes price as given in each instant. To abstract from problems of entry and exit, the number of firms if fixed at n.[5]

The production function of the firms is:

$$q = q(A(t), T(t), L(t), K(t))$$

where:

A = a vector of exogenous factors; and
T = technology index of the firm.

As discussed below, T is assumed to be a function of past R&D expenditures. The current research assumes that q is increasing and strictly concave in A, L, K, and T (where T embodies all current and past R&D expenditures). At any given time, the maximum possible T, denoted by $T^M(t)$, is a function of the basic research performed outside the industry. Any firm is able to obtain any $T \leq T^M(t)$ through the appropriate investment in R&D. The assumptions ensure an interior solution to the firm's problem

Technical change makes labor and capital more productive. An increase in T^M followed by applied R&D investment on the part of the firm lowers long-run average cost over all levels of output, thereby lowering the long-run equilibrium price. In other words $\partial p/\partial T < 0$. Because $Q = nq$ and $p(t) = p(nq(\cdot, \cdot, \cdot, \cdot))$, the direct effect of a change in the technology index on price is

[5]The generality of the results is not affected in the case where n is variable. Details are available from the author upon request.

(1) $\partial p/\partial T = n(\partial p/\partial Q)(\partial q/\partial T)$.

As the firm's technology index approaches $T^M(t)$, price approaches a lower limit $p^M(t)$ that is positive.

Technology depreciates if it is not maintained or as older innovations are displaced partially or totally by new innovations (Griliches, 1979; Pakes and Schankerman, 1984).[6] Consider the distinction between productivity-enhancing R&D and productivity-sustaining R&D. Productivity-enhancing R&D leads to gains in productivity (and downward shifts of average cost), while productivity-sustaining R&D allows maintenance, i.e., replaces the depreciated portion, of these gains. The former creates technologies that depreciate (in the sense that productivity falls and costs rise) as the inputs allowed by this technology become less productive or more expensive.[7] Within the model, one can think of productivity-enhancing R&D as the government's basic research that sets the upper limit $T^M(t)$ and as the firms' applied R&D that causes their technology indexes to rise in the direction of $T^M(t)$. To maintain the upper limit $T^M(t)$ once it is reached, firms must engage in productivity-sustaining R&D, perhaps in response to more basic productivity-sustaining R&D funded by government agencies.

[6]This depreciation has been assumed in empirical models of the effects of R&D since the pioneering work of Griliches (1964). More recent examples include Griliches and Mairesse (1984), Seldon (1987), and Suzuki (1985).

[7]Plucknett and Smith (1986) discuss productivity-sustaining research in agriculture. For example, gains in agricultural yield often are obtained through a single gene. The gains would be fleeting, however, if not for subsequent development of multiline varieties, identical except for the presence of different genes, to defend against pathogens that are able to circumvent the resistance of the original single gene. New fertilizers are effective in increasing yield, but they historically have become more expensive as they diffuse. The yield could not be sustained if not for ongoing research with alternative and less expensive fertilizers. Similarly, pesticides increase yields, but they become less effective as pests develop immunity. Maintenance research investigates alternative ingredients to which pests are not yet immune. In health care, the development of a new vaccine lowers the cost of treating particular ailments, but new vaccines performing essentially the same therapy must be developed periodically to overcome the increasing resistance of infections. In forestry, new equipment and processes allow increased production, but ongoing R&D investigates the use of the new equipment and processes with smaller trees as the stock of larger trees is depleted.

The Model of a Competitive Firm

Suppose there is a once-and-for-all increase in T^M. Firms engage in applied R&D to adopt the new technology and then engage in productivity-sustaining R&D.[8] A firm invests in R&D each instant with funds from its instantaneous cash flow, total revenue net of production cost.[9] Let C(t) represent cash flow, and let R(t) denote R&D expenditure at time T. T(0) is defined as $T(0) \equiv T_0$. Suppose the time path of the firm's technology index is determined by $\dot{T} = R(t) - \varepsilon T(t)$, where ε is the constant proportional depreciation rate on technology.[10] Competitive forces compel the firm to maintain $T \geq T_0$ or equivalently, $R(t) \geq \varepsilon T(t)$ through the carrot of possible profits and the stick of rising average costs. The problem of the firm is to choose the time path of L, K, and R to maximize

$$(2)\ V = \int_0^\infty e^{-it}[p(t)q(A(t),T(t),L(t),K(t)) - wL(t) - rK(t) - R(t)]dt$$

subject to

(3a) $\dot{T} = R(t) - \varepsilon T(t)$,

(3b) $\varepsilon T(t) \leq R(t) \leq C(t)$,

(3c) $T(0) = T_0$, and

(3d) $T(t) \leq T^M(t)$,

where:

V = discounted profit stream of the firm; and

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[8]The appendix analyzes the case where the firm realizes that numerous technological breakthroughs will occur; the results in the appendix are straightforward after the simple model in the text is developed.

[9]Because the firm is risk-neutral, uncertainty is not considered in the model. The inclusion of uncertainty would complicate notation, but would not change the main results of the model.

[10]The form of this differential equation follows Nerlove and Arrow (1962) and is common in previous studies of demand-shifting activities of firms with market power.

i = firm's time preference.

Because firms engage in R&D, $R(t) > 0$. Equation (2) is similar to the R&D problem considered by Nakao (1982), but the solution to equation (2) will differ from Nakao because the firm considered in this model is competitive.

There are no adjustment costs for labor and capital; at each instant the firm sets $p(\partial q/\partial L) = w$ and $p(\partial q/\partial K) = r$. These conditions implicitly yield the optimal levels $L^* = L(p, A, T, w, r)$ and $K^* = K(p, A, T, w, r)$. Substitute L^* and K^* in equation (2) and rewrite the firm's problem as

$$(4) \quad \max_{\underset{\sim}{R}} V = \int_0^\infty e^{-it}[\Phi(T; p, A, w, r) - R]dt$$

subject to equations (3), where $\underset{\sim}{R}$ is the time path of R. Time arguments are suppressed for convenience and Φ is the instantaneous cash flow of the firm. The term in brackets equals zero in the initial equilibrium and will equal zero in the steady state. Depreciation of technology will ensure that $R > 0$ in the steady state. Let p^M denote the price in the steady state that equates the bracketed term to zero.

The Hamiltonian expression for the firm's problem is

$$(5) \quad H(T, R, \lambda) = e^{-it}[\Phi(T; p, A, w, r) - R] + \lambda(R - \varepsilon T).$$

Although the firm treats price as given at any instant, it perceives the impact of technical change on price over time. By the envelope theorem, $\partial\Phi/\partial T = \partial(pq)/\partial T$. Then the necessary (and, under the concavity assumptions, sufficient) conditions on the optimal path are

$$(6a) \qquad \lambda = e^{-it};$$

$$(6b) \qquad -\dot{\lambda} = e^{-it}[(\partial p/\partial T)q + p(\partial q/\partial T)] - \lambda\varepsilon; \text{ and}$$

$$(6c) \qquad \dot{T} = R - \varepsilon T.$$

From the structure of the problem, it is clear that the optimal path will direct the firm toward T^M. This is true for all firms. Suppose to the contrary (and without loss of generality) that m firms in the industry had achieved the technology levels $T_1 \leq T_2 \leq \ldots \leq T_m < T^M$ where T_j is the technology level of the jth firm and $m \leq n$. This cannot be an equilibrium; for any $j \in \{1,2, \ldots, m\}$ it is in the jth firm's interest to increase T_j (even for $j = n$ when $T_n < T^M$) so that it is slightly greater than T_m, because the jth firm either would mitigate its losses or gain a temporary cost advantage (a further cost advantage for $j = n$ when $T_n < T^M$) and, in either case, increase its economic profits. Because this holds for any $T_1 \leq T_2 \leq ... \leq T_m < T^M$ and for any $m = 1, 2, ... , n$, equilibrium requires that $T_1 = T_2 = ... = T_n = T^M$.[11]

Suppose that at time $t = 0$ the upper limit on technology increases to T^M. Then any firm's technology index is less than T^M, and the firm is not on the optimal path. The nature of this particular problem is well known. Given the form of the problem and the fact that $T(0) < T^M$, the optimal solution off the equilibrium path is to take the most rapid approach to the path by setting $R(t) = C(t)$ until the path is obtained.[12] Once the firm has achieved T^M, the stationary state is reached and the optimal R&D expenditure is given implicitly by equations (6a), (6b), and (6c). In the stationary state when the firms have achieved T^M, each firm produces $q = q^M$ and sells the good at the stationary state price p^M.

From equation (6a), it can be seen that $\lambda = e^{-it}$; because this is an identity, both sides can be differentiated with respect to t to get $\dot{\lambda} = -ie^{-it}$. Inserting these results into equation (6b) yields

$$(7) \quad e^{-it}[(\partial p/\partial T)q + p(\partial q/\partial T) - \varepsilon\ ] = ie^{-it}, \text{ or}$$

$$p(\partial q/\partial T) = i\ + \varepsilon - (\partial p/\partial T)q.$$

The term on the left is the value of the marginal product of technology. The term $i + \varepsilon$ in condition (7) is similar to a result obtained by Nerlove and Arrow (1962, p. 134;) in their model of advertising: "if the firm invests a dollar [elsewhere] now and spends it on [R&D] later, it makes [i] and saves [ε]." This term is part of the marginal cost of R&D investment. An additional marginal cost of R&D investment is the foregone revenue in the next instant due to technical change. This term is positive for $T = T^M$ because, in the absence of R&D, price would rise as T depreciates. This explains the (positive) term $-(\partial p/\partial T)q$ as an addition to marginal factor cost.

The optimal level of R&D, $R^M(t)$, can be obtained by inverting equation (7) and multiplying by the output elasticity of T. This yields the optimal ratio of the R&D index to total sales revenue

[11] If the cost of R&D is sufficiently high for some firm, then it could be forced to exit the market. But the conclusion of the proof still holds for all firms remaining in the market.

[12] Most rapid approach paths are discussed in Kamien and Schwartz (1981, pp. 91-92 and p. 199).

(8) $T/pq = (T/q)(\partial q/\partial T)/[i + \varepsilon - (\partial p/\partial T)q]$.

The M superscript is omitted from the variables T, p, and q for notational ease.

On the optimal path T^M is achieved, and the firm engages only in productivity-sustaining research; hence

(9) $\dot{T} = 0 = R - \varepsilon T$ or $R^M(t) = \varepsilon T^M$.

Let $\beta \equiv \beta(T) \equiv (T/q)(\partial q/\partial T)$, the output elasticity of technology. Then substituting equation (9) into equation (8) and rearranging terms yields

(10) $R^M/\varepsilon = pq\beta/[i + \varepsilon - (\partial p/\partial T)q]$.

Using equation (1) and defining $\xi \equiv \xi\,(Q) \equiv \left|(\partial Q/\partial p)(p/Q)\right|$, which is the absolute value of (market) price elasticity of demand, the optimal ratio of R&D expenditures to sales can be obtained:

(11) $R^M/pq = \varepsilon\beta/[i + \varepsilon + (\beta/\xi)(pq/T)]$.

The condition for the optimal R&D/sales ratio is analogous to the static Dorfman-Steiner (1954) condition for the optimal ratio of advertising expenditures to sales in the case of monopoly and also the dynamic Nerlove and Arrow (1962) version of the Dorfman-Steiner condition. It may be tempting to state, in parallel with Nerlove and Arrow (1962, p. 140), that if the various elasticities and the ratio pq/T on the right side of the equation (11) are constant, then the optimal R&D/sales ratio will be constant. But the optimal R&D/sales ratio is constant under much more general conditions. Previous models generating optimal fixed percentage rules on the equilibrium path for firms with market power (such as Nakao, 1982 or Nerlove and Arrow, 1962) have involved log-linear demand curves. In contrast, because

$$\beta = (T^M/q^M)(\partial q/\partial T)\Big|_{T=T^M} \text{ and } \xi = -(p^M/nq^M)(\partial Q/\partial p)\Big|_{p=p^M},$$

equation (11) is constant on the equilibrium path in general. Hence the optimal rule of thumb is obtained on the equilibrium path under general conditions. Because the optimal rule of thumb holds generally for competitive firms and only when demand is log-linear for firms with market power, it is possible to develop a statistical test that exploits this difference to test the hypothesis that R&D is less variable in more competitive industries.

The appendix considers the case where T^M is expected to increase at various, but unknown, times in the future. Each time that T^M increases, the firm increases R&D expenditures to obtain the new T^M as quickly as possible. Whenever the firm obtains the latest technology, the steady-state results hold. Because productivity-enhancing breakthroughs occur infrequently, there are extended periods over which the results of this section are applicable.

Empirical Observations of R&D Allocation

This section presents data from the National Science Foundation (NSF) (1981, 1985) that are consistent with existence of rule-of-thumb R&D allocation in three competitive industries. This only suggests that some competitive industries appear to practice a rule-of-thumb allocation in R&D. But these data alone support neither the profit-maximizing hypothesis nor the satisficing hypothesis, because both result in observationally equivalent behavior. Results from profit-maximizing models of both competitive and noncompetitive industries are used to develop a test that could refute the profit-maximizing hypothesis.

Table 1 presents industry totals of firms' operating expenses for R&D (in their own laboratories and other firms' facilities) in food and kindred products (SIC 20); textiles and apparel (SICs 22 & 23); and lumber, wood products, and furniture (SICs 24 & 25) for years reported by the NSF (1981, 1985). The NSF data do not form a complete time series, and the table is limited to what the NSF reports: selected years between 1958 and 1980. These industries have concentration ratios that generally are regarded as indicating competition (43.6 percent, 31.9 percent and 23.2 percent, respectively, in 1972 according to the U.S. Department of Commerce (1986)).[13]

Table 2 presents the R&D/sales ratio in percentage form for food and kindred products; textiles and apparel; and lumber, wood products, and furniture for selected years from 1958 through 1980. The figures suggest that there were increases in R&D/sales between 1958 and 1963 for food and kindred products and textiles and apparel. These increases may have occurred in 1962 as a response to an investment tax credit. This tax credit subsequently was suspended in September 1966, restored in March 1967, and finally terminated in April

[13]Most of the data reported by the NSF are subject to some error due to the need to impute estimated data for companies that fail to supply information. The data presented in Table 1 have small imputation rates and are not subject to large errors.

1969.[14] The stability of the R&D/sales ratios is most strking in the period 1972-1980, when the tax credit effect may have passed.

A noticeable increase in the R&D/sales ratio occurred for lumber, wood products, and furniture between 1969 and 1970. This increase may be explained partly by an important institutional development. In the early 1960s, there was a shift in focus from more applied research to more basic research at the U.S. Forest Products Laboratory (FPL) (Nelson, 1971). Because the majority of government research in wood products is performed by or in conjunction with the FPL, this change in orientation forced private firms to conduct more of their own applied research, resulting in an increase in the R&D/sales ratio. The increase in the ratio between 1969 and 1970 may be explained, in part, by this institutional change.

The model of R&D allocation with numerous breakthroughs (see appendix) shows that the impact of technological change on the R&D/sales ratio is ambiguous. The ratio series for textiles and apparel (Table 2) is constant for years after 1972, despite productivity-enhancing breakthroughs that occurred in the 1970s (e.g., automated looms and laser beam fabric cutting). In contrast, the 1970 increase in the R&D/sales ratio in lumber, wood products, and furniture may be due, in part, to important innovations in the mid to late 1960s (e.g., new lathes and glue technologies and the subsequent development of particle board).

Testing the Variability of R&D/Sales

The constancy of the R&D/sales ratio in the perfectly competitive model is a result of the nature of competition; the equilibrium price (p^M) and the limit on the technology index (T^M) are beyond the control of the firm. Models of firms with market power (e.g., Nakao, 1982; Nerlove and Arrow, 1962) result in a constant R&D/sales ratio only for industries that face a log-linear market demand curve. Because the competitive model presented above suggests that the R&D/sales ratio is constant regardless of the functional form of the market demand curve, one would expect the R&D/sales ratio in competitive industries to be constant from one period to another. Because models of firms with market power suggest that the R&D/sales ratio is constant only for a special case, one would expect the R&D/sales ratio in noncompetitive industries to vary from one

[14]The tax credit encouraged firms to reclassify some expenditures as R&D (Mansfield, 1986, p. 190). This is consistent with the post-1969 figures, for termination of the tax credit did not necessarily encourage firms to reclassify those expenditures as non-R&D.

period to another (except for industries satisfying the special case).[15] Taken together, these models suggest that the variability of the R&D/sales ratio over any span of time tends to increase as the firm's control over price and technology, i.e., the firm's market power, increases. To test this hypothesis, measures of R&D/sales variation and market power are needed. The measure of R&D/sales variability (hereafter, the ratio variation or RV) is the coefficient of variation, the standard deviation divided by the mean, of the R&D/sales ratio for 13 industries from 1958 to 1980.[16] R&D /sales data are available from the NSF (1981, 1985). For each industry there is one RV observation measuring the variability from 1958 to 1980. Therefore, the data are cross sectional.[17]

The industries (defined at the two digit SIC code level) in the sample are food and kindred products; textiles and apparel; lumber, wood products and furniture; paper and allied products; chemicals and allied products; petroleum refining and related industries; rubber products; primary metals; fabricated metal products; machinery; electrical equipment; aircraft and missiles; and professional and scientific instruments.[18]

A popular measure of market power is the four firm concentration ratio. The four firm concentration ratio (hereafter CR4) is the ratio of the sales of the largest four firms in the industry to total sales in the industry. Unfortunately, CR4 data at the two digit SIC code level are not available. As an alternative, a proxy is constructed for the two digit level CR4 from a weighted average of four digit SIC industries using data from the U.S. Department of Commerce (1986).

[15]Although log-linear demand functions are often useful approximations for empirical analysis, it is unlikely that many demand functions take the log-linear form. More flexible demand functions (such as those generated by the translog model or the almost ideal demand system (AIDS) model) may be closer approximations of industries' underlying demand functions. For a critique of the log-linear model and discussions of the properties of translog and AIDS models, see Deaton and Muellbauer (1980, especially pp. 17-18 and pp. 60-82).

[16]The coefficient of variation, introduced by Pearson (1956), is useful as a relative measure of dispersion because it controls for different levels of R&D/sales among the industries. The statistic often is used, especially in financial economics (see, e.g., Ibbotson, Siegel, Love, 1985; and Mikhail and Shawky, 1979).

[17]The period 1958-1980 is chosen to maximize data points (the number of industries). If earlier or later years were included, several industries would have to be discarded because the NSF (1980, 1984) did not report several industries separately before 1958 or after 1980. There are only 13 industries in the sample.

[18]Textiles and apparel are different two digit industries. Likewise, aircraft and missiles have different codes. The NSF aggregates data for textiles and apparel and also aggregates data for aircraft and missiles because the technologies and R&D activities are related.

The weights are the ratios of the value of shipments (sales) at the four digit SIC code level to the sum of the value of shipments (sales) of all the four digit SIC code level industries within the two digit SIC code for which data are available. For the ith four digit industry in the kth two digit SIC code industry, the weight, W_{ik}, is

$$W_{ik} = VS_{ik} / (\sum_{j=1}^{N} VS_{jk}),$$

where:

VS_{mk} (m = i, j) = value of shipments for the mth four digit industry; and
N = number of two digit industries for which data are available.

Data for a few of the four digit industries within some of the two digit industry sample were not available, so these four digit industries could not be used in the calculation. Hence, although the CR4 measure is constructed from a relatively large sample of the relevant four digit industries, it is subject to error in an unknown direction. This error is assumed to be uncorrelated with the disturbance term in the regression equation. The weighted average concentration ratio for the kth two digit industry ($CR4_k$) is

$$CR4_k = \sum_{i=1}^{N} W_{ik}\, CR4_{ik}$$

where:

$CR4_{ik}$ = concentration ratio for the ith four digit industry contained within the kth two digit industry.

A concentration ratio representing market power within each two digit industry is needed for the period 1958 to 1980. A ratio for a year near the midpoint of the period can serve as a proxy for market power within the period. The CR4s of most of the undustries used in this study exhibit motonic trends for reported years from 1958 to 1980 (U.S. Department of Commerce, 1986), so data from one year near the midpoint should approximate the 23 year average.[19]

[19]An alternative would be to take an average for each two digit SIC code over the 23 year period, but the missing data problem is worse for earlier years—the 23 year average could be a noisier proxy than the average from one year near the midpoint.

Although 1969 is the midpoint year, data for that year are not published. Instead, 1972 is used, a year for which the U.S. Department of Commerce (1986) presents CR4 data.

Table 3 presents the CR4 and RV data for the 13 industries of the sample. These are the data that will be used in the empirical analysis. Table 3 also presents the mean R&D/sales ratio from 1958 to 1980. This ratio was used in the construction of the RV.

The one time 100 percent jump in the R&D/sales ratio of lumber, wood products, and furniture between 1969 and 1970 (Table 2) is unique among the data and may have been due to institutional factors. A dummy variable, D, is used for this industry where D = 1 for the lumber, wood products, and furniture industry, D = 0 otherwise.

RV is regressed on CR4 and D in separate linear and log-linear regressions to approximate the relationship between RV and market power. The hypothesis that R&D expenditures are allocated in a profit-maximizing manner would be supported if $\partial RV/\partial CR4 > 0$ (RV increases with market power).

The competing hypothesis is that rule-of-thumb behavior is a result of satisficing behavior in the face of uncertainty regarding R&D. This is a blanket hypothesis for all firms (see, for example, Hay and Morris, 1979; Mansfield, 1968) and implies that any variability of the R&D/sales ratio would be due to randomness. Allowing for seemingly random fluctuations in the R&D/sales ratio, the satisficing hypothesis can be stated in terms of the coefficient of variation RV: $\partial RV/\partial CR4 = 0$.

The hypothesis to be tested is that $\partial RV/\partial CR4 = 0$ against the alternative hypothesis that $\partial RV/\partial CR4 > 0$. OLS regression estimates yield the following results (with t-statistics in parentheses):

$$\underset{(0.632)}{RV = 0.035} + \underset{(2.061)}{0.003[CR4]} + \underset{(3.041)}{0.180[D]}$$
$$R^2 = 0.499$$

$$\log(RV) = \underset{(-2.857)}{-4.003} + \underset{(1.439)}{0.600[\log(CR4)]} + \underset{(2.381)}{1.034[D]}$$
$$R^2 = 0.363$$

Goldfeld-Quandt and Breusch-Pagan tests (1986) support the hypothesis of homoscedasticity for both equations.[20] In both equations, the coefficients

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[20]These tests were applied because the assumption of homoscedastic errors could be violated in the cross-sectional regressions. The Goldfeld-Quandt test (Kmenta, 1986, pp. 292-294) requires separating the sample into two groups and rerunning two regressions of the equation under consideration (in this paper, RV

associated with D are positive and significant at the 5 percent level (one tailed test), reflecting the one time 100 percent jump of R&D/sales in lumber, wood products, and furniture. In both equations, the coefficients associated with CR4 are positive and significant at the 10 percent level (one tailed test). Thus, the t tests support the alternative hypothesis that $\partial RV/\partial CR4 > 0$ instead of the null hypothesis that $\partial RV/\partial CR4 = 0$. This confirms that the variation of R&D/sales is directly related to market power. This confirmation in turn implies support for the profit-maximizing hypothesis and rejection of the satisficing hypothesis of R&D.

Conclusion

The fixed percentage rule of thumb for R&D allocation often is dismissed as satisficing behavior in the face of uncertainty. This bounded rationality assumption satisfies the requirement of simplicity suggested by Friedman (1986), but it does not offer any predictive power, which Friedman (1986, p. 127) suggests is "the only relevant test of the validity of a hypothesis."

Alternatively, it is possible to develop models in which the rule of thumb emerges as a necessary condition for long-run profit maximization. In this paper, such a model was developed for the previously neglected case of cost-reducing R&D in a competitive industry. Conclusions from this model, together with conclusions from previous models of firms with market power, suggest a statistical test of the hypothesis that the rule of thumb is profit maximizing. The results of the statistical test support the hypothesis. This evidence suggests that the rule of thumb is rational profit-maximizing behavior rather than satisficing behavior and is the first statistical evidence in the profit-maximizing/satisficing controversy. This paper suggests the need and indicates a direction for further research about profit-maximizing behavior in R&D allocation decisions.

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as a function of CR4 and D) using each of the two groups in turn. The ratio of the two sample disturbance variances resulting from these regressions is the F statistic upon which the test is based. For the Goldfeld-Quandt tests, the sample was separated into groups of the six smallest CR4s and the six largest CR4s (Table 3). The industry with the median CR4 (food and kindred products) is omitted in the Goldfeld-Quandt tests. The Breusch-Pagan test (Kmenta, 1986, pp. 295-296) involves regressing $e_i^2/\hat{\sigma}^2$ on the explanatory variables where e_i is the least squares residual and $\hat{\sigma}^2$ is the regression sum of squares of the original regression equation. Dividing the error sum of squares of this new regression by 2 gives the χ^2 statistic upon which the Breusch-Pagan test is based The tests failed to reject the null hypothesis that the error terms are homoscedastic. For the Goldfeld-Quandt tests, the F statistics were 1.21 and 1.04, respectively, against the critical value 6.39 (5 percent significance level). For the Breusch-Pagan tests, the χ^2 statistics for the two regression equations were 0.696 and 0.594, respectively, against the critical value 5.991 (5 percent significance level).

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Table 1
Industry Funding of R&D in Selected Industries for Selected Years, 1958-1980
(Nominal Dollars, in Millions)

Market	1958	1963	1967	1972	1974	1975	1976	1977	1978	1979	1980
Food & Kindred Products (SIC 20)	83	130	183	259	298	335	355	415	472	528	620
Textiles & Apparel (SICs 22 & 23)	26	30	57	61	69	70	82	83	89	101	115
Lumber, Wood Products, & Furniture (SICs 24 &25)	12	11	12	64	84	88	107	123	126	139	148

Source: Table B-2 in National Science Foundation, *Research and Development in Industry, 1984*, January 1985

SIC 20 includes meat products; dairy products; preserved fruit and vegetables; grain mill products; bakery products; sugar and confectionery products; fats and oils; beverages; and miscellaneous

SICs 22 & 23 include weaving mills for cotton, manmade fiber, and wool; narrow fabric mills; knitting mills; textile finishing; floor covering mills; yarn and thread mills; men's and boy's apparel; women's and misses' apparel; hats, caps, and millinery; children's outerwear; fur goods; and miscellaneous

SICs 24 & 25 include logging camps; sawmills and planing mills; millwork, plywood, and structural members; wood containers; wood buildings and mobile homes; furniture for household, office, and public buildings; partitions and fixtures; and miscellaneous

1

Table 2
R&D Expenditures as a Percent of Sales in Selected Industries for Selected Years, 1958-1980

Market	1958	1963	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Food & Kindred Products (SIC 20)	.3	.4	.5	.5	.4	.5	.5	.4	.4	.4	.4	.4	.4	.4	.4	.4
Textiles & Apparel (SICs 22 &23)	.3	.5	.5	.5	.6	.5	.5	.4	.4	.4	.4	.4	.4	.4	.4	.4
Lumber, Wood Products, & Furniture (SICs 24 & 25)	.4	.5	.3	.4	.4	.8	.7	.8	.7	.8	.7	.7	.8	.7	.7	.8

Source: Table B-19 in National Science Foundation, *Research and Development in Industry, 1980*, January 1981

Later issues of *Research and Development in Industry* do not include data for years after 1980 in the three industries included here

The sales figures used here are for goods sold to customers outside the firm. Intrafirm sales are excluded

2

Table 3
R&D/Sales, Variability of R&D, and
Measures of Competition for 13 Industries

Industry	Mean R&D/Sales 1958-1980 (%)	Coefficient of Variation R&D/Sales	Estimated Four Firm Concentration Ratio
Food & Kindred Products	.4000	.1118	32.6809
Textiles & Apparel	.4091	.1318	24.7659
Lumber, Wood Products, & Furniture	.6375	.2739	19.9100
Paper & Allied Products	.8818	.1114	28.8505
Chemicals & Allied Products	3.7727	.0934	35.3238
Petroleum Refining	.7545	.2167	32.1667
Rubber Products	2.1909	.1314	28.4825
Primary Metals	.7181	.1046	44.1909
Fabricated Metals	1.2818	.1592	30.9776
Machinery	4.5273	.0820	34.6220
Electrical Equipment	7.3818	.2124	50.6865
Aircraft & Missiles	15.7636	.2734	60.5605
Professional & Scientific Instruments	6.4727	.1203	49.2246

Appendix

Consider the case where T^M is expected to increase any number of times in the future, but the dates and the number of these breakthroughs are unknown. In particular, suppose there are jumps in $T^M(t)$ at times $t = t_1, t_2, \ldots, t_k$, but the value of k as well as the values of $t_1, t_2, \ldots, t_k$ are uncertain. To simplify notation, let $T^M(t) = T^t$ and define $t_0 \equiv 0$ and $t_{k+1} \equiv \infty$. Then the problem of the firm is to

$$\max_{\underline{R}} E(V) = E\left[\sum_{k=1}^{k+1}\left\{\int_{t_{k-1}}^{t_k} e^{-it}[\Phi(T; p, A, w, r) - R]dt\right\}\right]$$

where:

E['] is the expectation operator, subject to (3) where (3d) is replaced by

(A.1) $T(t) \leq T^t$.

The optimal solution would require the firm to act as if each increase in T^M were a one time occurrence. If the firm can realize T^t before the next breakthrough, the analysis of the once-and-for-all model suggests that the firm should approach T^t as rapidly as possible. But even if the next breakthrough occurs before the firm achieves T^t, the firm does best to approach T^t as rapidly as possible. Suppose, either before or after the firm has achieved T^t, that the next breakthrough occurs so that the upper limit on the technology index is now T^{t+1}. As long as the firm is as close to T^t as was possible, it also will be as close to T^{t+1} as is possible. Hence, the firm does best to treat each breakthrough as a once-and-for-all change.

If breakthroughs occur infrequently, then there will be different steady states over different time intervals. In any particular steady state, the ratio of R&D expenditures to total revenue is given by equation (11), but the ratio could change as breakthroughs occur. Recall that $R^M = \varepsilon T^M$ on the equilibrium path, so that the sign of $\partial(R/pq)/\partial T$ coincides with the sign of $\partial(T/pq)/\partial T$. Because equation (8) is an identity,

(A.2) $\partial(T/pq)/\partial T = \{pq - T[(\partial p/\partial T)q + p(\partial q/\partial T)]\}/(pq)^2$

where:

$T = R^M/\varepsilon$ on the equilibrium path.

The sign depends on the sign of $pq - T[\partial p/\partial T)q + p(\partial q/\partial T)]$. From equation (1) and the fact that $Q = nq$, the numerator is

$$pq - [Q(\partial p/\partial Q) + p]T(\partial q/\partial T).$$

A breakthrough may be modest (in the sense that $\partial q/\partial T$ is relatively small) or important (in the sense that $\partial q/\partial T$ is relatively large). As a breakthrough is more modest, $\partial q/\partial T$ approaches zero, the numerator approaches pq, and the right side of (A.2) approaches $(pq)^{-1}$. If, in addition, total industry sales (pq) are large relative to R&D expenditures (which is usually the case, see Table 3), the change in the R&D/sales ratio would be relatively small. In that case, the ratios may be fairly close over several steady states. If the breakthrough is important, the second term in the numerator cannot be ignored because it is larger in absolute value, and the sign of $\partial(T/pq)/\partial T$ may be positive or negative depending on the relative sizes of various elasticities.

Productivity-enhancing breakthroughs seem to occur infrequently, and there have been extended periods where productivity has been stable. For example, Plucknett and Smith (1986) report that yields of wheat, sorghum, potatoes, cotton, sugar beets, field beans, and peanuts have been level in the U.S. since breakthroughs for the various crops occurred in the 1950s and 1960s. Scherer (1984) reports similar findings for 18 industries and classifies only three as still rapidly evolving. Hence there presumably would be extended periods with stable R&D/sales ratios in many industries. In addition, if the breakthroughs are modest and/or price elasticity is close to unity, there would be stable ratios even with technical change.