RAND Journal of Economics
Vol. 24, No. 2, Summer 1993

Underinvestment and incompetence as responses to radical innovation: evidence from the photolithographic alignment equipment industry

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Neoclassical theory suggests that when an industry is shaken by radical technological change, incumbent firms will be replaced by entrants because entrants have greater strategic incentives to invest in radical innovation. Organizational theory suggests that incumbent firms fail in the face of radical innovation because they fall prey to inertia and complacency. I show that if organizational effects are significant, tests of neoclassical theory in isolation will yield spurious or noisy results. Using data derived from a detailed field study of the photolithographic alignment equipment industry, I show that as neoclassical theory predicts, established firms invested more than entrants in incremental innovation, but that in agreement with organizational theory, the research efforts of incumbents seeking to exploit radical innovation were significantly less productive than those of entrants.

1. Introduction

■ The relative superiority of large, established firms in the introduction and development of technological innovation has been a subject of debate since at least the work of Schumpeter. Schumpeter initially suggested that small, entrepreneurial firms were likely to be the source of most innovation (Schumpeter, 1934), but he subsequently claimed that large established firms possessing some degree of monopoly power were likely to be the driving force behind technical progress (Schumpeter, 1950). He suggested that their superior access to capital and skilled labor, in combination with their ability to effectively appropriate innovation, gave them considerable advantages over small firms and new entrants.

Subsequent research in this field has had contradictory or fragile results. Cross-sectional studies of the relationship between firm size, market power, and innovative activity have in general found no systematic relationship (Baldwin and Scott, 1987; Cohen and Levin, 1989), and theoretical work in the area has been similarly inconclusive, generating results that are extraordinarily sensitive to the core assumptions of the model employed. (Baldwin and Scott (1987) and Reinganum (1989) provide excellent summaries of this literature.)

In this article I suggest that one of the sources of this confusion may be the failure to

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I would like to thank Dataquest Inc. and VLSI Research, Inc., for generous permission to use their published data, and many individuals throughout the photolithographic alignment industry who gave generously of their time to this research. Richard Caves, Kim Clark, Iain Cockburn, Dietmar Harhoff, Bruce Kogut, Manuel Trajtenberg, and two anonymous referees were very helpful, but any errors or omissions remain entirely my responsibility. The research described here was funded by the Division of Research, Harvard Business School. Its support is gratefully acknowledged.

integrate theories of heterogeneous research capability into neoclassical theories of investment behavior. Existing neoclassical theory suggests that entrants will replace incumbent firms during periods of radical technological change because they have greater strategic incentives to invest in radical innovation, while organizational theory suggests that established firms often fail in the face of radical innovation because their research efforts are significantly less productive than those of entrants. Using a model that incorporates both strategic and organizational effects, I show that when innovation that is "radical" in the economic sense is also "radical" in the organizational sense, the two theories cannot be empirically distinguished. Moreover, when innovation is "incremental" in the economic sense but "radical" in the organizational sense, a test of either theory that fails to control for the other will yield spuriously negative or noisy results.

I test this idea using data from the history of the semiconductor photolithographic alignment equipment industry. Using a database that includes research costs, sales, and organizational and technical information for every product-development project initiated by every firm in the photolithographic alignment equipment industry between 1960 and 1986, I show that the failure of many established firms in the industry cannot be understood without examining both underinvestment and incompetence as responses to radical innovation. I show that the data are consistent with systematic differences in research productivity between incumbents and entrants. Once these differences are controlled for, the history of investment and of realized commercial success in the industry is consistent with both neoclassical theories of investment behavior and organizational theories of heterogeneous research capability. These results highlight the danger of assuming that there is any simple relationship between market power, size or experience, and innovative success, and they open up a number of important issues concerning the role of organizational capabilities in strategic competition.

The article begins by synthesizing the existing literature to develop a model that integrates neoclassical theories of investment behavior with organizational theories of research capability. Section 3 discusses the data, Section 4 describes the photolithographic alignment equipment industry, and Section 5 presents the empirical results.

2. Framework for analysis

■ **Theories of investment behavior.** The fruitfulness of the distinction between incremental and radical innovation as a basis for understanding the response of large established firms to innovation was recently demonstrated in a well-known debate initiated by Gilbert and Newbery (1982) and Reinganum (1983). A seminal article by Arrow (1962) suggested that firms in competitive markets have significantly greater incentive to invest in innovation than do firms in markets characterized by a significant degree of monopoly power. Gilbert and Newbery suggested that this result holds only if entry is blockaded. They showed that if there is free entry to the industry, incumbent firms with monopoly power will rationally preempt potential entrant investment in innovation in order to continue to profit from the extension of existing market power to a new generation of technology. But Reinganum reinstated Arrow's result by showing that under conditions of uncertainty, incumbent monopolists will rationally invest less in innovation than entrants will, for fear of cannibalizing the stream of rents from their existing products.

Subsequent research established that whether incumbent monopolists or entrants have greater incentives to invest in innovation is a function of the degree to which innovation destroys existing market power and of the uncertainty surrounding the innovative process (Gilbert and Newbery, 1984a and 1984b; Reinganum, 1984; Salant, 1984; and Bresnahan, 1985). Gilbert and Newbery's (1982) result holds if the date at which an innovation will be introduced is not contingent upon any single firm's investment and if the innovation is incremental in the sense defined by Arrow (1962), that is, if the older technology remains a viable substitute for the new. Under these conditions, incumbents have more incentive to invest in innovation than entrants do, and if all firms have homogeneous research capabilities, then on average incumbent firms with market power will retain their dominant position in an industry whose technology evolves incrementally. However, if the date at which the new technology will be introduced is not contingent on incumbent investment and the innovation is radical (or drastic in Arrow's sense, in that it makes the old technology quite obsolete), then both incumbents and entrants have equivalent incentive to invest in it.[1] Intuitively, Gilbert and Newbery's result is driven by the fact that incumbents have an incentive to extend their monopoly power when an innovation is incremental, but have no opportunity to do so when an innovation is sufficiently radical.

Reinganum's (1983) result, in contrast, holds when an innovation is radical, or drastic in Arrow's sense, and when the date at which it will be introduced is a function of investments made by each firm. If an incumbent's investment increases the probability that an innovation will be introduced, then at the margin, incumbents with market power will have less incentive to invest in innovation than entrants. Intuitively, an incumbent's investments have a lower marginal rate of return than those of entrants, since they increase the probability that their existing stream of rents will be cannibalized. If entrants and incumbents have homogeneous research capabilities, Reinganum's model suggests that entrants will displace incumbent firms when innovation in the industry is sufficiently radical. She shows that the balance of incentives in the case in which innovation is incremental but surrounded by uncertainty is a function of the relative strength of the fear of cannibalization and the incentive to extend market power (Reinganum, 1989).

These results are summarized in Figure 1. They illustrate graphically the utility of a careful distinction between incremental and radical innovation for the understanding of the investment behavior of incumbents and entrants. A parallel stream of research in the organizational tradition suggests that the distinction is also a source of insight into the differences between the research capabilities of entrants and established firms.

FIGURE 1

STRATEGIC INCENTIVES FOR INVESTING IN INNOVATION

	Implications for existing market power?	
	Innovation makes the existing technology obsolete	Innovation competes directly with the existing technology
	$P_m^n < C^o$	$P_m^n > C^o$
Dependence on incumbent investment?		
Introduction date independent of incumbent investment	? Incumbents and entrants have equivalent incentives to invest	"Incremental" innovation Incumbents have a greater strategic incentive to invest
Introduction date a function of incumbent investment	"Radical" innovation Entrants have the greater strategic incentive to invest	? Investment behavior depends on the balance of incentives

Note: P_m^n is the monopoly price of the new technology and C^o is the marginal cost of the old.

[1] Arrow defined an innovation as "drastic" if it represents such an advance that the older technology is no longer a viable substitute. In the case of process innovations, the formulation used by Arrow, this is equivalent to the assumption that $P_m^n < C^o$, where P_m^n is the monopoly price of a product using the new process technology and C^o is the cost of the product using the old process technology. For product innovations, the equivalent condition is that demand for the old technology falls to zero upon the introduction of the new even when the new is introduced at its monopoly price.

□ **Theories of research capability.** The suggestion that large, established firms and small, newly founded entrants should have heterogeneous research capabilities dates back at least to Schumpeter. He suggested that on balance, larger firms would be better positioned than new entrants to take advantage of innovation, since they have preferential access to information and skilled personnel (Schumpeter, 1950). This idea is elaborated in the work of Chandler (1990), who stressed the importance of scale and scope economies in research and the advantage that they give to the modern multinational corporation. Mowery's (1989) research into the structure and importance of the major research corporation and Freeman's (1982) summary of the institutionalization of research both underline the importance of scale and experience in the successful exploitation of modern technology.

However, the presumption that, all other things equal, established firms are more likely to be able to exploit new technologies than are smaller, newer firms has been increasingly tempered by the recognition that in some circumstances extensive experience with a technology may be a substantial disadvantage (Hedberg, 1981; Hannan and Freeman, 1984; Tushman and Anderson, 1986). In several industries, large and experienced firms have found it very difficult to respond effectively to entry both by new, small companies founded by aggressive entrepreneurs and by large, established companies that have gained experience in related fields.[2]

The key to reconciling these seemingly contradictory observations lies in understanding the quite different implications of radical and incremental innovation for the evolving information-processing capabilities of the firm. Large established firms have an advantage over entrants in the pursuit of incremental innovation because incremental innovation builds upon their existing knowledge and capabilities, but these assets can simultaneously reduce substantially the effectiveness of their attempts to exploit radical innovation.

Information is costly to acquire and use (Simon, 1955 and 1959). Firms facing repetitive tasks develop assets that reduce this cost (Cyert and March, 1963). Arrow (1974) suggested that in stable environments, firms will rationally invest in "communication channels" and "information filters" that reduce the cost of processing routine information. Nelson and Winter (1982) suggested that firms develop "routines" or "procedures" in response to their experience, and these codify the knowledge of the firm. Similarly, contingency theorists such as Burns and Stalker (1966), Galbraith (1973), and Daft (1982) have suggested that large firms in stable environments develop "mechanistic" organizational structures that enable them to cope quickly and effectively with their environment. This process is evident in the patterns of organizational evolution described by Chandler (1962) and is well described in Mintzberg (1979).

These assets are a source of considerable advantage as long as innovation in an industry remains "incremental" or "competence enhancing." Incremental innovation, in this context, is defined as routine, predictable change that is a logical extension of existing knowledge. It is often of considerable economic importance and may be difficult and expensive (Enos, 1962; Hollander, 1965), but the organizational procedures and routines and the information filters that guide the established organization allow it to exploit incremental innovation faster and more effectively than is possible for entrants or for less-experienced firms.

The same assets, however, may significantly reduce the research productivity of established firms attempting to exploit innovation that is "radical" in the sense of "competence destroying." In this context, an innovation is radical if it requires the firm to process quite different kinds of information. The information filters and organizational procedures and

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[2] General Electric, despite its vast size and years of experience in vacuum tubes, never became a major player in the semiconductor business despite heavy investment, and more recently both IBM and DEC have had considerable difficulty extending their existing skills to the rapidly growing market for workstations. In all three cases, the historical experience of the company in the previous generation of the technology appears to have substantially reduced the effectiveness of its research (Braun, 1978).

routines that have developed through the firm's experience with a sequence of incremental innovations founded upon quite different scientific or technological principles become partially obsolete. If this obsolescence goes unrecognized, or if the costs of developing a more appropriate set of assets are greater than the costs of using an existing set, then the research productivity of established firms pursuing radical innovation will be significantly lower than that of entrants (Abernathy, 1978; Burns and Stalker, 1966; Clark and Fujimoto, 1992). Arrow (1974) suggested that established firms may continue to use existing information-processing assets, despite their lower efficiency, because the cost of developing a new set is greater than the penalties of using less-efficient assets. Thus Arrow's work suggests that incumbent productivity may be lower than entrant productivity for any particular project, but that the incumbent will avoid the setup costs incurred by new entrants. Nelson and Winter (1982) and a number of the organizational theorists, in contrast, have suggested that incumbents continue to use unsuitable information-processing assets because organizational change is difficult to effect and very risky (Hannan and Freeman, 1984). A considerable body of empirical work confirms the usefulness of this perspective (Clark, 1988; Dewar and Dutton, 1986; Tushman and Anderson, 1986).

□ **Integrating theories of investment behavior with theories of research capability.** These two streams of research—the first focusing on the implications of market power for investment in radical and incremental innovation, and the second focusing on the implications of historical experience for the ability to exploit radical and incremental innovation—have qualitatively similar implications for the relative performance of established firms and new entrants as long as innovation that is incremental in the economic sense is also incremental in the organizational sense. They both suggest that established firms are likely to dominate incremental innovation, while entrants are likely to dominate radical innovation.

These qualitatively similar conclusions may explain why, in general, existing empirical and theoretical research has not explored the interaction between the two effects. We do not know if incumbent firms routinely dominate incremental innovation because they have greater incentives to invest in it or because they can exploit it much more effectively than entrants can. Similarly, we do not know if most technological breakthroughs are introduced by entrants because they have a greater strategic incentive to invest in them or because their research efforts are much more effective than those of incumbents. Economists who have explored the role of heterogeneous firm capabilities in industry evolution have generally failed to distinguish between radical and incremental innovation (Jovanovic, 1982; Ericson and Pakes, 1989), and organizational behaviorists have in turn neglected to consider the role of strategic investment behavior in explaining relative organizational success. Empirical work either has not distinguished between the two effects or has explored only comparative investment levels or comparative capability. (See, for example, work reported in Acs and Audretsch (1988), Ettlie, Bridges, and O'Keefe (1984), Griliches (1984), Moch and Morse (1977), and Pavitt (1987), or the excellent summary of the literature given in Cohen and Levin (1989).) Below I illustrate the potential importance of this distinction through the development of an analytic model that captures both effects.

□ **Model formulation and hypothesis development.** In order to fix ideas and to frame hypotheses for the empirical work, it is helpful to introduce some formal notation into the discussion. Consider the case of a firm with experience E and market power M investing an amount R in research. Let the expected net benefit from investing in research, Π, be given by

$$\Pi(R, M, E) = \sigma(R, E, a) \cdot \beta(M, b) - C(R), \tag{1}$$

where $\sigma(R, E, a)$ is the probability that the research will be successful, $\beta(M, b)$ is the discounted net benefit of introducing a successful product, and $C(R)$ is the cost of undertaking the research. Define a and b as other factors that affect the probability of being successful and the profitability of the innovation, respectively.

Then Gilbert and Newbery's (1982) insight that an incumbent's existing market power allows it to benefit more from an incremental innovation than entrants would can be captured by defining

$$\beta_I^i > \beta_E^i, \qquad \frac{d\beta_I^i}{dM} > 0, \tag{2}$$

ceterus paribus, where subscripts indicate benefit to the incumbent or entrant, respectively, and superscripts indicate the type of innovation.[3] Similarly, Reinganum's (1983) insight can be captured by defining

$$\beta_I^r < \beta_E^r, \qquad \frac{d\beta_I^r}{dM} < 0. \tag{3}$$

Under the traditional neoclassical assumption that firms have homogeneous capabilities, or that σ is invariant across firms, equation (1) collapses to

$$\Pi(R, M, E) = \sigma \cdot \beta(M, b) - C(R). \tag{4}$$

Then, for the case of single incumbents facing single entrants, both Gilbert and Newbery's and Reinganum's results are easily derived:

$$R_I^i > R_E^i, \qquad \Pi_I^i > \Pi_E^i, \qquad R_I^r < R_E^r, \qquad \Pi_I^r < \Pi_E^r, \tag{5}$$

$$\frac{dR_I^i}{dM} > 0, \qquad \frac{d\Pi_I^i}{dM} > 0, \qquad \frac{dR_I^r}{dM} < 0, \qquad \frac{d\Pi_I^r}{dM} < 0. \tag{6}$$

Turning now to the organizational theories discussed above, define

$$\frac{d\sigma_I^i}{dE} > 0, \qquad \frac{d\sigma_I^r}{dE} < 0, \tag{7}$$

or, all else equal, the probability of being successful increases with experience if the research is incremental but decreases with experience if the research is radical, or competence destroying.[4]

Under the implicit assumption characteristic of much research in the organizational tradition that strategic or economic effects are of secondary importance, so that the expected net benefit of successful innovations is the same for all firms, equation (1) collapses to

$$\Pi(R, M, E) = \sigma(R, E, a) \cdot \beta - C(R), \tag{8}$$

and one can straightforwardly derive the "stylized facts" predicted by the organizational literature:

$$\Pi_I^i > \Pi_E^i, \qquad \Pi_I^r < \Pi_E^r. \tag{9}$$

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[3] To simplify the discussion, I assume that innovations that are "radical" or "incremental" in their implications for investment behavior satisfy the two criteria derived from Gilbert and Newbery's and Reinganum's work—that is, I assume that a radical innovation is "drastic" in the sense that the older technology cannot compete with it and "radical" in the sense that investment by an incumbent increases the probability that it will be introduced. An empirical application of the results will, as a result, be contingent on this actually being the case. See Figure 1.

[4] Economists may find the idea that a firm's experience may reduce the odds of success puzzling, since in principle an established firm could "simply" duplicate the research capabilities of an entrant through the creation of a new venture or a "skunk works." The available empirical work, however, suggests that historical experience positively handicaps the firm in cases of radical innovation (Tushman and Anderson, 1986; Clark, 1988). One possible explanation is that information filters derived from historical experience "blind" the firm to the nature of radical innovation (Arrow, 1974). See the discussion above.

Under the assumption that firms rationally anticipate their probable research productivity, one can further derive

$$R_I^i > R_E^i, \qquad R_I^r < R_E^r \tag{10}$$

and

$$\frac{dR_I^i}{dE} > 0, \qquad \frac{d\Pi_I^i}{dE} > 0, \qquad \frac{dR_i^r}{dE} < 0, \qquad \frac{d\Pi_I^r}{dE} < 0. \tag{11}$$

A comparison of equations (5) and (6) with equations (9), (10), and (11) illustrates the dangers of attempting to test the validity of either perspective without explicitly controlling for the other. For if innovations that are incremental in the economic sense are also incremental in the organizational sense, and vice versa, and if market power is closely correlated with experience, organizational and strategic effects will reinforce each other, both theories predict the same outcomes, and it will be impossible to identify the role of the two separately.

Moreover, if innovations that are incremental in the economic sense may be either incremental or radical in the organizational sense, and vice versa, testing the validity of one set of theories without controlling for the other may yield spuriously noisy or even negative results. Figure 2 demonstrates this by combining equations (5), (9), and (10).

If, for example, a test of the economic theories happens to use a sample of innovations that are all incremental in the organizational sense, the results may reject the hypothesis that incumbents invest less than entrants in radical innovation. Incumbents will indeed have a smaller strategic incentive to invest in innovation that is radical in an economic sense, but the expectation that their research efforts will be more productive may balance or even outweigh the strategic effect.

Notice that the integration of these two perspectives also suggests that a simple comparison of investment levels or realized profitability alone cannot validate either of the two perspectives. One possible approach is to compare the marginal influence of market power and experience on levels of investment and realized profitability. Figure 3 shows the results of combining equations (6) and (11) for an incumbent firm.

Thus if both economic and organizational effects are important, a robust test of the neoclassical hypotheses requires the use of a sample that includes "off-diagonal" innovations—innovations that are incremental in one sense and radical in the other—and controls for both historical market power and historical experience.

As a first step in this direction, this article presents a study of the role of strategic investment incentives and heterogeneous organizational capability in the evolution of the semiconductor optical photolithographic alignment equipment industry. Since its founding

FIGURE 2

If, in the economic sense, innovation is:	If, in the organizational sense, innovation is: Incremental	Radical
Incremental	$R_I > R_E$, $\Pi_I > \Pi_E$ Incumbent's research is more productive and expected benefits are greater	R_I ? R_E, Π_I ? Π_E Incumbent's research is less productive, but expected benefits are greater
Radical	R_I ? R_E, Π_I ? Π_E Incumbent's research is more productive, but expected benefits are smaller	$R_I < R_E$, $\Pi_I < \Pi_E$ Incumbent's research is less productive and expected benefits are smaller

FIGURE 3

If, in the economic sense, innovation is:	If, in the organizational sense, innovation is: Incremental	Radical
Incremental	$\frac{dR_I}{dM} > 0, \frac{dR_I}{dE} > 0$ $\frac{d\Pi_I}{dM} > 0, \frac{d\Pi_I}{dE} > 0$	$\frac{dR_I}{dM} > 0, \frac{dR_I}{dE} < 0$ $\frac{d\Pi_I}{dM} > 0, \frac{d\Pi_I}{dE} < 0$
Radical	$\frac{dR_I}{dM} = 0, \frac{dR_I}{dE} > 0$ $\frac{d\Pi_I}{dM} = 0, \frac{d\Pi_I}{dE} > 0$	$\frac{dR_I}{dM} = 0, \frac{dR_I}{dE} < 0$ $\frac{d\Pi_I}{dM} = 0, \frac{d\Pi_I}{dE} < 0$

in the early 1960s, the photolithographic alignment industry has been shaken by four waves of major innovation. In each case the innovations were incremental in the economic sense but radical in the organizational sense, and each saw the successful entry of new firms and the failure of most of the established firms to maintain their position. The history of research and competition in the industry thus presents an ideal opportunity to explore the importance of organizational effects in competition and to test the validity of both the neoclassical and organizational hypotheses.

3. The data

■ The data for this study were collected during an eighteen-month, field-based study of the photolithographic alignment equipment industry conducted from the spring of 1987 to the summer of 1988. The core of the data is a panel dataset consisting of research and development costs and sales revenue, by product, for every product-development project conducted in the industry's history.[5] These data are supplemented by a detailed managerial and technical history of each project. Forty-nine product development projects undertaken by nineteen firms were identified during the course of the research. In order to avoid the sample selection bias that would result if firms that tried to enter the industry and failed were omitted from the dataset, a variety of strategies were used to ensure that every development project undertaken in the industry's history, including those undertaken by failed entrants, was included.[6] The data were drawn from a wide variety of sources, including internal firm records, field interviews, the trade press, published consulting reports, and industry experts. Multiple sources were used wherever possible to validate the data.[7]

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[5] A "product-development project" was defined as any research project that the firm itself described as being designed to introduce a new model. Data were collected using the product-development project as the unit of analysis, since reliable data describing spending on research and development by project by year by firm could not be obtained.

[6] The trade journal *Solid State Technology,* which follows the industry and has been published monthly since 1960, lists all new products announced in the field. Data were collected about every product or prototype announced through this listing (which is free). In addition, throughout the 18 months of the data-collection effort, all respondents were asked to direct the researcher to other firms and individuals who had also been active in the industry. The industry's technical community is very small—even today, about 50 engineers dominate the technology—and I believe the dataset to be a comprehensive one.

[7] In those cases in which it was possible to contact individuals with firsthand knowledge of a project, interview data were combined with internal firm records and with data obtained from market research and consulting firms to construct a written history of each project and of each firm's involvement in the industry. This history was then circulated to those who had been interviewed and to other knowledgeable individuals in order to confirm the data's validity. In the few cases where it proved impossible to interview anyone involved with a project, the project's history was constructed through secondary sources and through interviews with industry experts.

No quantitative information was collected about basic scientific research relevant to the industry conducted either within university or government labs or within firms active in the industry. Discussions with industry experts suggested that although such research was occasionally important, it diffused quickly through the industry's technical community and was not an important source of competitive advantage. It proved to be difficult to obtain comprehensive price or cost data, since the price of an aligner is negotiated between the supplier and the customer and since each sale includes a different bundle of product options.

4. The industry

■ Optical photolithographic aligners are pieces of capital equipment used in the manufacture of solid-state semiconductor devices.[8] Aligners are sold directly to semiconductor device manufacturers. They usually represent at least 30% of the cost of a new semiconductor facility, and their performance is critical to its success. The choice of aligner is thus a major decision for the customers, who have historically been governed by three major criteria: compatibility with an installed base, technical performance, and price.

A semiconductor device manufacturer incurs considerable switching costs in changing from one aligner vendor to another.[9] Thus they almost always continue to buy aligners from their current vendor for the simple expansion of existing capacity. A move to a new vendor is a major decision that is usually considered only when a manufacturer is developing an entirely new product line or building an entirely new facility. But since semiconductor technology evolves very rapidly, this is not an infrequent event. New production capacity of this type can be roughly divided into two markets: leading-edge production, mostly dynamic random access memories (DRAMs), and less-demanding applications such as the production of integrated circuits.

Photolithographic aligners are very sophisticated pieces of equipment whose performance at the limits of their capabilities cannot be fully predicted, and the highly competitive nature of the semiconductor industry historically has meant that customers investing in leading-edge production capability have been willing to pay a considerable price premium for aligners that offered marked improvements in performance. However, in the segments of the semiconductor industry that are technically less demanding, and in those cases in which two or more vendors have offered leading-edge equipment with matched capabilities, the price of the equipment has been a more important factor in the purchase decision. Although the lack of systematic cost data, combined with the difficulty of determining the full value in use of new aligners, makes it difficult to measure the extent to which the rents generated by major innovations were captured by the alignment equipment producers, the available evidence suggests that successful innovation was extremely profitable and that successful innovators captured a significant share of available rents.

On the one hand, competition between the customers for alignment equipment, the semiconductor chip producers, has historically been very intense. A succession of powerful

[8] The production of integrated circuits requires the transfer of a sequence of very small, intricate patterns to the surface of a silicon wafer in a series of layers. The transfer process is known as "lithography." In optical lithography the surface of the wafer is coated with a light-sensitive chemical known as a "resist." The pattern that is to be transferred to the wafer surface is drawn onto a "mask" and the mask is used to block light as it falls onto the resist, so that only those portions of the resist defined by the mask are exposed. The resist is developed and the exposed areas are stripped away, leaving the mask pattern on the wafer. This pattern is then used as the basis for further processing of the wafer through deposition or etching. The process may be repeated as many as 25 times during the manufacture of a semiconductor device. Photolithographic alignment equipment is used to position the mask relative to the wafer, to hold the two in place during exposure, and to expose the resist. A more detailed description of the technology is given in Henderson (1988).

[9] "Masks" developed for use on one vendor's aligner can rarely be transferred to another's. In addition, since the operation of an aligner is a difficult and sophisticated operation, operators, engineers, and maintenance technicians must all be retrained at considerable expense.

entrants in combination with substantial overcapacity throughout much of the semiconductor industry's history have kept margins very lean, and it is unlikely that the semiconductor device manufacturers exerted any significant monopsony power over the photolithographic alignment equipment producers. On the other hand, the available evidence suggests that the leading alignment equipment suppliers were very, very profitable over the period covered by the study. In the 1960s, Kulicke & Soffa, the leading supplier, had gross margins reported to be on the order of 30–40%, as did Kasper and Cobilt, the firms that succeeded Kulicke & Soffa as industry leaders (Henderson, 1988). The scanner was rumored to be the most profitable product ever introduced by Perkin-Elmer, the diversified firm that introduced it, and in the four years following GCA's introduction of the stepper, sales of the small diversified company more than tripled while net income nearly quintupled. Margins probably came under greater pressure with the entry of a number of major Japanese suppliers in the early 1980s, but the competitive significance of alignment technology to the semiconductor device manufacturers, in combination with the highly competitive nature of the semiconductor business, makes it likely that prior to 1986, the period covered by the study, successful alignment equipment producers were still able to capture a significant fraction of the value created by their innovations.

Both the established firms in the alignment equipment industry and the entrants to it have shown considerable variation in size, experience, and structure. Table 1 briefly describes some of the firms that introduced the more important photolithography products in the period 1960–1985. Although single-product, venture-capital-funded startups played a major role in the industry in the early years, for the last 15 years the industry has been dominated by diversified firms of considerable size and resources, and entrants into the industry have been firms that have gained experience in related technologies. Both incumbents and entrants appear to have enjoyed ready access to development capital. In the early years the very high margins realized on successful products attracted considerable venture capital, and industry maturity has seen development funded by major corporations with substantial financial resources.

Alignment equipment is technically sophisticated, and technical change in the industry has been rapid. The first aligners were introduced in the early 1960s. They were built by teams of two or three designers and cost less than $5,000. In contrast, a modern aligner can cost as much as $2 million, and its design can occupy the energies of more than a hundred engineers for several years. A steady stream of incremental innovation has been responsible for much of the improvement in alignment performance, but the industry has been shaken by four major innovations over the last 25 years. Table 2 gives descriptions of each of them.

These innovations have had dramatic competitive consequences. In each case, they saw the replacement of the industry leader by an entrant—despite the fact that a cursory

TABLE 1 Major Product Introductions in Photolithography, 1960–1985

Year	Aligner Type	Quoted Resolution (microns)	Firm
1962	Contact	9–15 (?)	Kulicke & Soffa (Small U.S. instrumentation/optics firm)
1969	Contact	2–3	Kasper Instruments (U.S. venture-capital-funded startup)
1974	Proximity/contact	5–6	Kasper Instruments
1974	Scanner	2.5	Perkin-Elmer (A diversified U.S. company with a significant precision optics division)
1978	Scanner	.9–1.25	Perkin-Elmer
1978	Step and repeat (1)	1.5–2.0	GCA (U.S. small diversified conglomerate)
1982	Step and repeat (2)	1.1–1.25	GCA
1982	Step and repeat (2)	1.0	Nikon (Large diversified Japanese corporation)
1986	Step and repeat (2)	.6–.9	Nikon

TABLE 2 Summary of Major Innovations in Photolithography

Contact printer	Mask and water are held in contact during exposure. Uniform pressure across mask and wafer and accurate alignment is critical.
Proximity printer	Mask and wafer are separated during exposure. Accuracy and stability of gap-setting mechanism are crucial to performance.
Scanning projection aligner	Image of mask is projected onto wafer by scanning reflective optics. Interactions between lens and other components are critical to successful performance.
First-generation stepper	Image of mask is projected through refractive lens. Image is "stepped" across the wafer on a precision "stage." Relationship between lens field size and source emerge is a significant determinant of throughput. Depth of focus characteristics—driven by relationship between source wavelength and lens numerical aperture—constrain performance.
Second-generation stepper	Introduction of "site by site" alignment, so that mask and wafer are aligned at every step. Larger 5× lenses. Throughput is driven by calibration and stepper stability; relationship between lens and mechanical systems becomes an increasingly critical means of controlling distortion.

analysis would suggest that these innovations were far from "radical" in that established firms in the industry had a number of important advantages in the development and dissemination of major innovations, and that the majority of the established firms invested heavily in the technology necessary to develop them. What happened? The empirical analysis that follows suggests that the history of the industry is best understood through the explicit integration of theories of investment behavior with theories of heterogeneous research capabilities. While established firms invested substantially more in research than entrants did, they were significantly less effective in their efforts to bring products based on major innovation to commercial success.

5. The empirical analysis

■ The model developed above suggests that in order to construct a valid test of either neoclassical theories of investment behavior or organizational theories of heterogeneous research capability, one should explicitly distinguish innovation that is incremental in an economic sense from innovation that is incremental in an organizational sense, and one's sample of innovations should include some that are incremental in one sense and not in the other, or vice versa. The model also suggests that it is important to control for strategic and organizational effects by using measures of historical market power and historical experience.

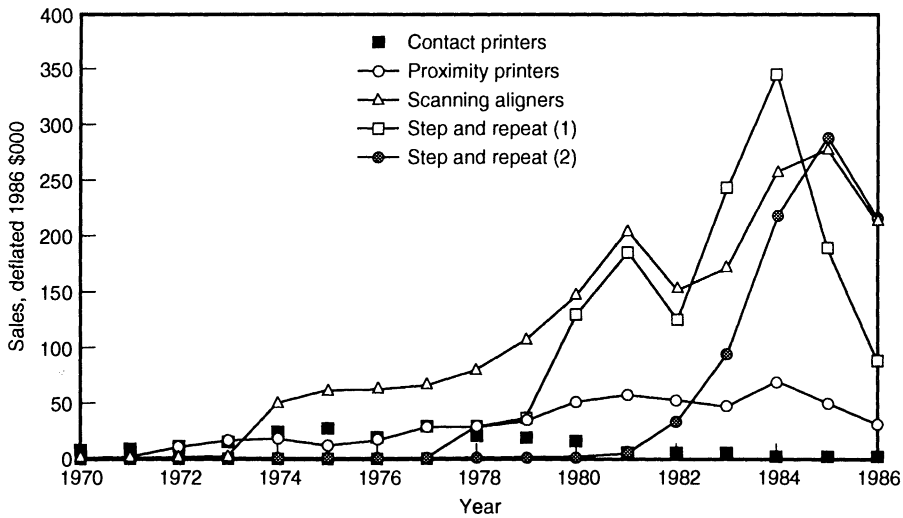
Accordingly, I begin the empirical analysis with a discussion of radical and incremental innovation in photolithography. I show that innovation in optical lithography has been incremental in the economic sense but both radical and incremental in the organizational sense. I then show that the pattern of investment and commercial success is consistent with the presence of significant differences in research capabilities between entrants and incumbents. I use measures of historical market power and experience to control for these differences, and I show that, at least in photolithography, the data support both Gilbert and Newbery's hypothesis that incumbents have a greater strategic incentive to invest in incremental innovation than entrants and the organizational hypothesis that incumbents were significantly less effective than entrants in their attempts to develop and commercialize innovation that was radical in the organizational sense.

□ **Radical and incremental innovation in photolithography.** Innovation in optical photolithography has consistently been incremental in the economic sense relevant to Gilbert and Newbery's and Reinganum's work. Recall that Gilbert and Newbery focused attention on the degree to which an innovation competes with the existing technology, and they defined an innovation as "incremental" if the older technology remains an important substitute and thus if demand for the innovation increases with the price of the older technology. In the case of photolithography, both qualitative and quantitative evidence suggests that even the major technological innovations have competed actively with the previous generation of equipment. The first models to incorporate the new technology in every generation were stringently evaluated against the older technology. Semiconductor device manufacturers ran "bake offs" in which the two technologies were evaluated side by side, and in several well-known cases the older-generation aligner was chosen over the new even in extremely demanding applications.[10] Both generations of equipment also competed actively in the less-demanding segments of the market, in which the proven performance and lower price of the older technology usually gave it a very considerable advantage. As Figure 4 shows, sales of the older generations of equipment remained significant despite the introduction of the newer technologies.

Table 3 presents the results of a hedonic analysis of product price. (Details of variable definition and descriptive statistics are given in Appendixes A and B). Although these results should be treated with great caution, since matched price and performance characteristics could be obtained only for a limited sample of projects, they are consistent with the hypothesis that technological innovation in the industry was incremental in Gilbert and Newbery's sense. Product price was regressed on a dummy variable set to one if the product was introduced in the first year that the technology it embodied was introduced, resolution (the key technical characteristic of an aligner), and dummy variables for each generation of the technology. If major innovation in photolithography were radical or drastic in Arrow's sense, in that it replaced the existing technology completely, one would expect each generation to command a unique price premium over the previous generation. However, with the possible exception of contact aligners, aligner price is significantly correlated with resolution,[11] not with technological generation.[12]

FIGURE 4

SALES OF ALIGNMENT EQUIPMENT



[10] The most well-known example of this is IBM's choice to continue to use the scanning projection aligner in the production of DRAMs despite the widespread adoption of the step and repeat aligner by its competitors.

[11] Price is negatively correlated with resolution, since higher-performing aligners have *smaller* resolutions—they are capable of producing finer lines on the wafer surface.

[12] The significance of the dummy "contact aligner" may reflect the fact that modern contact aligners are used almost exclusively in leading-edge research, rather than in semiconductor manufacturing. Although they can resolve smaller lines than any of the other generations of photolithographic equipment, their very low yields make them unsuitable for use in large-scale manufacturing applications.

TABLE 3 Hedonic Analysis of Aligner Price
Dependent variable: Lg (*PRICE*)
Ordinary least squares, 28 observations.

	(1)	(2)
Intercept	6.69***	6.60***
	(.13)	(.28)
FIRST PRODUCT	.19	.15
	(.39)	(.38)
Lg (*ALIGNER RESOLUTION*)	−1.44***	−1.89***
	(.13)	(.38)
CONTACT		1.18*
		(.64)
PROXIMITY		.72
		(.49)
STEP AND REPEAT, FIRST GENERATION		.42
		(.28)
STEP AND REPEAT, SECOND GENERATION		.04
		(.38)
Adjusted R^2	.82	.84

Standard errors in parentheses.
* Significant at the 10% level.
** Significant at the 5% level.
*** Significant at the 1% level.

Innovation in photolithography also appears to have been incremental by the definition relevant to Reinganum's conclusions, although this is more difficult to show. On the one hand, the industry is a small one, and to the degree that semiconductor device manufacturers perceived a new generation of technology to be more risky than the last, it is possible that the participation of established firms in the new generation would increase its credibility and the probability of its successful introduction. On the other hand, since aligner performance is so critical to competitive advantage in the semiconductor industry, potential customers avidly evaluated every new technology, seemingly irrespective of the size or experience of the firm introducing it. Moreover, the key technological innovations underlying each new generation of equipment were widely available some years before they were first incorporated into products. It is thus difficult to accept that established firms would believe that their own research would increase the probability of successful introduction of a new generation of technology. Interview data also suggests that, at least qualitatively, fear of product cannibalization was not a constraint in the formulation of established firms' product-development strategies.

Thus, innovation in photolithography appears to have been incremental in the economic sense defined by Gilbert and Newbery and by Reinganum. Given the considerable market power probably exercised by successful incumbents in the industry, one would expect incumbent firms to have significantly greater strategic incentives to invest in innovation than entrants, all other things equal.

A careful exploration of the implications of innovation within the industry for the capabilities of established firms suggests, however, that all other things were far from equal. Each of the major innovations in optical photolithography technology has been "radical" in the organizational sense. Each made obsolete some of the most critical organizational knowledge of the established firms. The detailed data underlying this conclusion is outlined in Henderson and Clark (1990) and Henderson (1988), but a brief sketch of the argument and some illustrative examples are presented below.

Photolithographic aligners consist of a number of components knit together into a complex, interdependent product. The design of a new aligner requires both knowledge of the intricacies of individual component design—"component knowledge"—and knowledge of the ways in which these components can be most effectively integrated—"architectural knowledge." In photolithography, the former has been held by individuals and the latter has been the property of the design group as a whole. The innovations that created so much turmoil in the photolithographic alignment industry did so because they made obsolete much of the architectural knowledge of the established firms. Since this knowledge was deeply embedded in the routines and procedures of the firm, its obsolescence proved to be very difficult to observe, and many of the established firms continued to rely on obsolete architectural knowledge in the design of the next generation of equipment.

Consider, for example, the experience of Kasper Instruments. Kasper was founded in 1968, and by 1973 it was a small but profitable firm supplying approximately half of the market for contact aligners. In 1973 the firm introduced the first contact aligner to be equipped with proximity capability, but widespread use of proximity aligners did not occur until the introduction and general adoption of Canon's proximity aligner in the late 1970s.

The proximity aligner was not a radical technological advance, but it is one in which quite a different set of relationships between components is critical to successful performance. Kasper's failure to understand the obsolescence of its knowledge of these relationships and its consequent failure to design adequately performing proximity aligners is illustrated graphically by two incidents.

The first is the firm's interpretation of early complaints about the accuracy of its gap-setting mechanism. In proximity alignment, misalignment of the mask and the wafer can be caused both by inaccuracies or instability in the gap-setting mechanism and by distortions introduced during processing. Kasper attributed many of the problems that users of its proximity equipment were experiencing to processing error, since it believed that processing error had been the primary source of problems with its contact aligner. The firm "knew" that its gap-setting mechanism was entirely adequate and, as a result, devoted very little time to improving its performance. In retrospect this may seem like a wanton misuse of information, but it represented no more than a continued reliance on an information filter that historically had served the firm well. The second illustration is provided by Kasper's response to Canon's initial introduction of a proximity aligner. The Canon aligner was evaluated by a team at Kasper and pronounced a copy of a Kasper machine. The team had employed the criteria the firm used for evaluating its own aligners—criteria that had been developed during its experience with contact aligners. The technical features that made Canon's aligner a significant advance, particularly the redesigned gap-setting mechanism, were not observed because they were not considered important.

Similar problems are evident in all four episodes of major innovation in the industry's history. The case of Perkin-Elmer and stepper technology is a case in point. By the late 1970s, Perkin-Elmer had achieved market leadership with its scanning projection aligners, but the company failed to maintain its position when stepper technology came to dominate the industry in the early 1980s. In evaluating the two technologies, Perkin-Elmer's engineers accurately forecast the progress of individual components in the two systems but failed to see how new interaction in component development—including better resist systems and improvements in lens design—would give stepper technology a decisive advantage. GCA, the company that took leadership from Perkin-Elmer, was itself supplanted by Nikon, which introduced a second-generation stepper. Echoing Kasper, GCA first pronounced the Nikon stepper a copy of its own design. Even after GCA fully recognized the threat posed by the second-generation stepper, it was handicapped by its historical experience in its attempts to develop a competitive machine. GCA's engineers were organized by component, and cross-department communication channels were structured around the architecture of the first-generation system. While GCA engineers were able to push the limits of the component technology, they had great difficulty understanding the advances in component integration that had given Nikon's aligner its superior performance.

There is thus considerable reason to believe that organizational effects had significant competitive implications for the evolution of the photolithographic alignment industry. Since innovation in the industry was consistently incremental in the economic sense but both radical and incremental in the organizational sense, the industry thus provides an ideal setting in which to explore the importance of organizational variables in innovative competition and to test the validity of some of the organizational and economic hypotheses current in the literature.

□ **Are organizational effects important?** As a first step in the analysis, the results presented in Tables 4 and 5 test for the presence of organizational effects in the data. All innovation in the industry was assumed to be incremental in the economic sense based on the discussion above. Following my analysis of the way in which accumulated experience in any single generation of alignment technology put firms attempting to develop products in the next generation at a substantial disadvantage, projects which represented a firm's first attempt to introduce a product in a new generation were defined as radical in the organizational sense. (Details of variable construction and descriptive statistics are given in Appendixes A and B.)

Focusing first on levels of investment and expected profitability, recall from Figure 2 that when innovation is incremental in the economic sense and in the organizational sense, $R_I > R_E$ and $\Pi_I > \Pi_E$; when innovation is incremental in the economic sense and radical in the organizational sense, R_I ? R_E and Π_I ? Π_E. Table 4 presents the results of testing these hypotheses using investment in research as the dependent variable, while Table 5 presents the results using share of market as a proxy for realized profitability as the dependent variable.[13] Since the presence of unobserved firm effects suggests that the unobserved errors are almost certainly correlated across the two equations, the results presented in Table 4 were estimated using two-stage least squared techniques, and the results presented in Table 5 were estimated with predicted values of research investment derived from the results reported in Table 4 used in place of observed values. Tobit analysis was used to analyze the determinants of share of market, since 6 of the 49 projects in the sample were never commercially introduced.

Consider first the results presented in Table 4. Investment in research was proxied by person-years of engineering time invested in the first three years of the project. Since the real costs of engineering person-years certainly vary across firms and over time, a dummy variable, *DIVERSIFIED FIRM,* was included to control for gross differences in the costs of research between more diversified and single-product firms. This variable also controls for possible differences in access to research capital between the two types of firm. The arguments suggesting that large firms might be able to devote more resources to research because of their preferential access to capital were summarized above.[14] *DIVERSIFIED FIRM* proved to be consistently positive and significant, suggesting that on average, diversified firms invested nearly twice as much in research as startup or single-product firms did, but the interaction of diversity with entry proved to be insignificant.

Two measures of demand—average sales of semiconductor devices for the three years following the product's introduction (or the project's termination, if no product was introduced commercially) and the percentage increase in sales of semiconductor devices the year that the project was initiated—were included in the regressions to capture the effects of anticipated demand on the value of a new product introduction. Since the costs of switching photolithographic equipment types within a continuing manufacturing operation are very

[13] Prior market share was used as the best available measure of existing market power. Alternative measures, such as cumulative prior sales, were also explored. None changed the significance of the reported result.

[14] Several authors have also suggested that diversified firms may have advantages, in addition to their size, in their ability to operate an internal capital market and to transfer resources effectively across businesses, although it has been suggested that, particularly in the semiconductor-related sectors, the availability of venture capital in combination with an active and informed labor market has given small startup firms the advantage.

TABLE 4 **Testing for Organizational Effects**
Dependent variable: Lg (*RESEARCH INVESTMENT*)
Two-stage least-squared analysis, 49 observations.

	(1)	(2)
Intercept	4.10**	4.33***
	(1.62)	(1.59)
Lg (*DEMAND*)	−0.15	−0.13
	(0.33)	(0.32)
Lg (% *INC IN DEMAND*)	0.09*	0.07
	(0.05)	(0.05)
Lg (1/*NUM COMPETING PROJECTS*)	0.72	0.82*
	(0.49)	(0.49)
DIVERSIFIED FIRM	0.71**	0.60**
	(0.28)	(0.28)
CONTACT & PROXIMITY	−0.55	−0.62
	(0.44)	(0.43)
STEP & REPEAT	1.07**	1.15***
	(0.43)	(0.42)
INCUMBENT	0.75**	
	(0.29)	
*INCUMBENT*INCREMENTAL*		0.89***
		(0.30)
*INCUMBENT*RADICAL*		0.40
		(0.35)
Adjusted R^2	0.54	0.56

Standard errors in parentheses.
* Significant at the 10% level.
** Significant at the 5% level.
*** Significant at the 1% level.

high, I expected investment in new-product development to be correlated with the expansion of demand rather than with demand levels per se, particularly for new entrants. In that event, the rate of increase in sales proved to be marginally significant across all specifications, and it was no more significant for entrants than for incumbents. The use of alternative measures of demand produced very similar results.

Two dummy variables, *CONTACT & PROXIMITY* and *STEP & REPEAT* were introduced to control for the technical complexity of the project, since all else equal, the costs of research should increase with increasing sophistication of the underlying technology. Both variables had the expected sign and *STEP & REPEAT* was consistently significant, suggesting that, as expected, research became more costly as the technological complexity of the aligners increased.

The expected effects of competition on investment are ambiguous, and theoretical models offer no clear predictions (Baldwin and Scott, 1987). On the one hand, increased competition may increase incentives to invest if firms perceive themselves to be participating in a "race." On the other hand, increased competition may reduce the average return on successful projects. A variety of alternative measures of competition was explored, including total competitive investment in research, competitors' sales, and competitors' share of sales in the final market. None proved strongly significant. The results reported here measure competition as the inverse of the number of competitive research projects in the relevant generation of equipment, since this is a variable many theoretical models have suggested is likely to be important (Reinganum, 1989).

Specification (1) tests Gilbert and Newbery's hypothesis, neglecting any possible organizational effects. The results are quite consistent with Gilbert and Newbery's work, suggesting that incumbents in photolithographic alignment equipment have invested significantly more than entrants in research. Indeed, substituting in mean values of the relevant variables, these results suggest that all other things equal, incumbents invested nearly twice as much as entrants. A traditional economic analysis that neglected the role of organizational effects might stop here, accepting this result as evidence consistent with neoclassical theories of investment behavior.

Specification (2) tests for the presence of organizational effects by distinguishing between projects that were radical and incremental in the organizational sense, and it demonstrates the dangers inherent in neglecting this perspective. The results are consistent with the presence of a powerful organizational effect. For while incumbents invested significantly more than entrants in projects that were incremental in both the economic and organizational sense, the data do not reject the hypothesis that incumbents and entrants invested the same amount in projects that were incremental in the economic sense but radical in the organizational sense, all other things equal. Substituting in mean values of the variables suggests that incumbents invested over 60% more resources in projects designed to introduce incremental innovation than they did in projects designed to introduce radical innovation. Thus, incumbent firms appear to have rationally anticipated less-productive research efforts when they invested in innovation that was radical in the organizational sense, and thus to have invested no more than entrants despite the fact that they could expect successful innovation to be more profitable for them than it would have been for entrants. This is exactly the result expected when both economic and organizational effects are present.

The results presented in Table 5 are similarly consistent with the presence of a strong organizational effect. Specification (1), which tests Gilbert and Newbury's hypothesis as a traditional analysis might, without distinguishing between projects that are radical and in-

TABLE 5 **Testing for Organizational Effects**
Dependent variable: Lg (*SHARE OF MARKET*)
Tobit analysis, 49 observations.

	(1)	(2)
Intercept	1.07	1.85
	(1.08)	(1.11)
Lg (1/*NUM COMPETING PROJECTS*)	0.04	0.25
	(0.27)	(0.26)
DIVERSIFIED FIRM	0.22	0.17
	(0.21)	(0.19)
*ESTIMATED RESEARCH EFFORT**	0.11	−0.05
(*CONTACT & PROXIMITY*)	(0.31)	(0.33)
*ESTIMATED RESEARCH EFFORT**	0.06	−0.05
(*SCANNING PROJECTION*)	(0.24)	(0.26)
*ESTIMATED RESEARCH EFFORT**	0.00	−0.05
(*STEP & REPEAT*)	(0.20)	(0.20)
INCUMBENT	−0.18	
	(0.19)	
*INCUMBENT*INCREMENTAL*		−0.05
		(0.23)
*INCUMBENT*RADICAL*		−0.45***
		(0.16)
Log-Likelihood for Weibull	−22.3	−19.5
Scale parameter for Weibull	0.32	0.29
	(0.04)	(0.04)

Standard errors in parentheses. *ESTIMATED RESEARCH EFFORT* is constructed using specification 2 in Table 4.
* Significant at the 10% level.
** Significant at the 5% level.
*** Significant at the 1% level.

cremental in the organizational sense, rejects it altogether in that there is no evidence that incumbents were able to translate historical market power into larger market share. Specification (2), which controls for organizational effects, confirms that one of the reasons that Gilbert and Newbery's hypothesis is rejected is that there are very significant organizational effects at work. Although there is still no evidence that incumbents obtained a larger share of market than entrants when they introduced products that were incremental in both the economic and organizational sense, the size of the standard error on the relevant coefficient is enormous, suggesting that the data may reject Gilbert and Newbery's hypothesis simply because of the small size of the sample. The coefficient on *INCUMBENT* RADICAL*, in contrast, is negative and very significant, suggesting that, all other things equal, incumbents have obtained a smaller share of the market for new products incorporating innovations that were radical in a technological or organizational sense, or that the research efforts of incumbents attempting to develop products that incorporated major or competence-destroying innovation in photolithography were significantly less productive than those of entrants. This result is in line with the raw data. On average, entrants obtained more than 50% of the market in the three years immediately following their introduction of a radical innovation. Radical innovations introduced by incumbents obtained less than 7% of the market.

Together these results suggest that organizational effects have been critically important in the history of competition in photolithography. From the model developed above, this implies that in photolithography, the predictions of neoclassical theories of investment behavior can be differentiated from theories of heterogeneous research capability only through a comparison of the marginal effects of market share and experience on investment and commercial success.

Recall the top row of cells in Figure 3: When innovation is incremental in the economic sense and in the organizational sense,

$$\frac{dR_I}{dM} > 0, \qquad \frac{dR_I}{dE} > 0, \qquad \frac{d\Pi_I}{dM} > 0, \qquad \text{and} \qquad \frac{d\Pi_I}{dE} > 0.$$

When innovation is incremental in the economic sense and radical in the organizational sense,

$$\frac{dR_I}{dM} > 0, \qquad \frac{dR_I}{dE} < 0, \qquad \frac{d\Pi_I}{dM} > 0, \qquad \text{and} \qquad \frac{d\Pi_I}{dE} < 0.$$

Tables 6 and 7 present the results of an attempt to test these hypotheses by separately identifying economic and organizational effects using share of market in the previous generation as a measure of established market power and cumulative investment in research as a measure of prior experience.

Table 6 explores the effects of market power and experience on investment in research. Specification (1) tests the hypothesis that the effects of historical market share and prior experience are significantly different when innovation is incremental or radical in an organizational sense, and specification (2) tests the hypotheses of Figure 3. Investment is significantly correlated with prior market share, and its effects are not significantly different depending on whether the innovation is incremental or radical in the organizational sense, just as the economic theory predicts. The insignificance of the coefficients on prior experience, in contrast, suggests either that the organizational theory can be rejected or that my measures of market share and prior experience are too closely correlated (Pearson correlation coefficient .44) to enable me to identify the two effects separately.

Table 7 explores the influence of market power and experience on realized share of market. Here again, specification (1) tests the hypothesis that the effects of historical market share and prior experience are significantly different when innovation is incremental or radical in an organizational sense, and specification (2) tests the hypotheses of Figure 3.

TABLE 6 **Disentangling Economic and Organizational Effects**
Dependent variable: Lg (*RESEARCH INVESTMENT*)
Two-stage least-squared analysis, 49 observations.

	(1)	(2)
Intercept	4.15**	4.15**
	(1.60)	(1.60)
Lg (*DEMAND*)	−0.09	−0.09
	(0.32)	(0.32)
Lg (% *INC IN DEMAND*)	0.07	0.07
	(0.05)	(0.05)
Lg (1/*NUM COMPETING PROJECTS*)	0.79	0.79
	(0.48)	(0.48)
DIVERSIFIED FIRM	0.59**	0.59**
	(0.28)	(0.28)
CONTACT & PROXIMITY	−0.60	−0.60
	(0.44)	(0.44)
STEP & REPEAT	1.22***	1.22***
	(0.43)	(0.43)
Lg (*HISTORICAL MARKET POWER*)	0.17*	
	(0.09)	
Lg (*HISTORICAL MARKET POWER*)∗*INCREMENTAL*		0.17*
		(0.10)
Lg (*HISTORICAL MARKET POWER*)∗*RADICAL*	0.06	0.10
	(0.17)	(0.15)
Lg (*PRIOR EXPERIENCE*)	0.08	
	(0.09)	
Lg (*PRIOR EXPERIENCE*)∗*INCREMENTAL*		0.08
		(0.09)
Lg (*PRIOR EXPERIENCE*)∗*RADICAL*	−0.08	0.00
	(0.13)	(0.12)
Adjusted R^2	0.56	0.56

Standard errors in parentheses.
* Significant at the 10% level.
** Significant at the 5% level.
*** Significant at the 1% level.

These results provide partial support for both the economic and the organizational hypotheses. Realized market share is positively correlated with historical market power only in the case of innovations that were radical in the organizational sense, providing only partial confirmation of Gilbert and Newbery's hypothesis. Prior experience is significantly and negatively correlated with realized market share for radical innovation, providing strong support for the hypothesis that incumbents attempting to introduce products that require quite different organizational capabilities were severely handicapped by their store of experience. But incumbent success in introducing incremental innovation is insignificantly correlated with prior experience, raising difficult questions for our understanding of firm capability, since the organizational theory discussed above implies that incumbent experience should be a source of competitive advantage in the pursuit of incremental innovation.

This result may reflect the unavoidable sample-selection bias that results from it being impossible to include potential entrants that chose not to enter the industry in the sample. While all the activities of the incumbent firms are included in my sample, only those entrants who initiated product-development work could be included. If some potential entrants developed (unobserved) capabilities through experience in related fields that enabled them to exploit incremental innovation in photolithography, while others were dissuaded from entry because of the incumbent firms' extensive experience, my results will be skewed by my observation of the former but not the latter.

TABLE 7 **Disentangling Economic and Organizational Effects**
Dependent variable: Lg (*SHARE OF MARKET*)
Tobit analysis, 49 observations.

	(1)	(2)
Intercept	1.45	1.45
	(1.04)	(1.04)
Lg (1/*NUM COMPETING PRODUCTS*)	0.11	0.11
	(0.26)	(0.26)
DIVERSIFIED FIRM	0.28	0.28
	(0.17)	(0.17)
*ESTIMATED RESEARCH EFFORT**	−0.02	−0.02
(*CONTACT & PROXIMITY*)	(0.23)	(0.23)
*ESTIMATED RESEARCH EFFORT**	−0.05	−0.05
(*SCANNING PROJECTION*)	(0.18)	(0.18)
*ESTIMATED RESEARCH EFFORT**	−0.05	−0.05
(*STEP & REPEAT*)	(0.17)	(0.17)
Lg (*HISTORICAL MARKET POWER*)	0.01	
	(0.06)	
Lg (*HISTORICAL MARKET POWER*)**INCREMENTAL*		0.01
		(0.06)
Lg (*HISTORICAL MARKET POWER*)**RADICAL*	0.17*	0.18*
	(0.10)	(0.09)
Lg (*PRIOR EXPERIENCE*)	−0.01	
	(0.05)	
Lg (*PRIOR EXPERIENCE*)**INCREMENTAL*		−0.01
		(0.05)
Lg (*PRIOR EXPERIENCE*)**RADICAL*	−0.20***	−0.21***
	(0.08)	(0.06)
Log-Likelihood for Weibull	−18.45	−18.45
Scale parameter for Weibull	0.28	0.28
	(0.04)	(0.04)

Standard errors in parentheses.
* Significant at the 10% level.
** Significant at the 5% level.
*** Significant at the 1% level.

6. Discussion and conclusions

■ This article has suggested that one of the roots of the confusion surrounding the discussion of the competitive implications of radical and incremental innovation may be a failure to integrate theories of heterogeneous capability into neoclassical or strategic theories of investment behavior in the face of innovation.

Using a dataset derived from the history of the photolithographic alignment equipment industry that includes innovations that were incremental in their economic implications but both radical and incremental in their implications for the capabilities of established firms, I showed that the history of investment and commercial success in the industry is consistent with the presence of significant differences in research productivity between firms. Although a test of Gilbert and Newbery's (1982) hypothesis that does not control for organizational effects does not reject their hypothesis, differentiating between innovations that are radical and incremental in the organizational sense increases the power of the test and suggests that the research efforts of incumbent firms attempting to introduce innovations that were radical in the organizational sense were significantly less productive than those of entrants. When historical market share and cumulative research were used to control for historical market power and accumulated experience, respectively, the results provided partial support for both neoclassical theories of investment behavior and organizational theories of research capability. Incumbents invested more in incremental innovation and gained a larger market share as a function of historical market power, and they were significantly less productive than entrants in their attempts to introduce innovations that were radical in the sense that they made their existing capabilities obsolete.

Given the limited range of the data, these results can be suggestive only. Two directions may prove particularly fruitful for further research. The first is the extension of the analysis to other industries, together with the development of superior measures of organizational capability and anticipated market power. The finding that incumbents appear to have been no more productive than entrants in the development of incremental innovations is particularly puzzling and should be explored in other contexts. The second is the refinement of our existing theoretical understanding of this issue. This research suggests that we may need much better models of heterogeneous capability—its evolution and its role in competition—if we are to fully understand the competitive implications of technological change.

Appendix A

■ **Variable Definitions.**

RESEARCH INVESTMENT	Person-years invested in development during the first three years of development. Person-years was used as a measure of investment both because the raw data were collected in this form and because its use avoids the need to deflate investment costs. Since currently available indices of research costs are of questionable validity, this is a major advantage. The major drawback to this measure is its implicit assumption that the real costs of a person-year invested in development have been constant over time and across firms. To the extent that the real wages of research personnel have increased over time and the real costs of employing people in small, startup firms are lower than they are in a larger firm with higher overheads, this assumption will be incorrect.
SHARE OF MARKET	Average share of market, first three years after aligner introduction, or for all of the years in which the product was available, if it did not survive three years.
PRICE	Product price in thousands of 1986 dollars.
DEMAND	Average worldwide sales of semiconductor devices, in 1986 dollars, over the first three years after the product's introduction, or after the development project was terminated if a product was not introduced.
PRIOR EXPERIENCE	Cumulative person-years invested by the firm in the previous generation, if the innovation was radical, and in this generation, if the innovation was incremental.
1/NUM COMPETING PROJECTS	Inverse of the number of other development projects initiated by competitors in this generation of equipment.
HISTORICAL MARKET POWER	Share of market in the previous generation, if the innovation was radical, and in this generation, if the innovation is incremental.
ALIGNER RESOLUTION	Manufacturer's specification for the minimum feature size capability of the aligner, in microns.
% INC IN DEMAND	Percentage increase (decrease) in worldwide sales of semiconductor devices, in constant dollars, the year that the development project was initiated.
DIVERSIFIED FIRM	A dummy variable set equal to one if the firm sold products other than semiconductor photolithographic alignment equipment. This variable does not divide the data into incumbents versus entrants or Japanese versus American firms. Although all the Japanese firms that entered the industry were diversified, so were many of the American and European firms, and both diversified and undiversified firms entered the industry successfully. Throughout the analysis, *DIVERSIFIED FIRM* had significantly greater explanatory power than a variable distinguishing between Japanese and non-Japanese firms.
INCUMBENT	A dummy variable set equal to one if the firm had previously introduced an aligner.
FIRST PRODUCT	A dummy variable set equal to one if this was the first product introduced in its generation.
RADICAL	A dummy variable set equal to one if the innovation was "radical" with respect to the firm's organizational capabilities.

INCREMENTAL	A dummy variable set equal to one if the innovation was "incremental" with respect to the firm's organizational capabilities.
CONTACT	A dummy variable set equal to one if the project was designed to introduce a contact aligner.
PROXIMITY	A dummy variable set equal to one if the project was designed to introduce a proximity aligner.
SCANNING PROJECTION	A dummy variable set equal to one if the project was designed to introduce a scanning projection aligner.
STEP AND REPEAT, FIRST GENERATION	A dummy variable set equal to one if the project was designed to introduce a first-generation stepper.
STEP AND REPEAT, SECOND GENERATION	A dummy variable set equal to one if the project was designed to introduce a second-generation stepper.

Appendix B

■ **Descriptive Statistics.**

Variable	Mean	Standard Deviation	Minimum	Maximum
RESEARCH INVESTMENT	55.1	59.3	3.0	250.0
SHARE OF MARKET	27.8	30.1	1.0	100.0
PRICE	509.0	389.8	10.6	1467.0
DEMAND	20.2	10.0	3.31	38.0
PRIOR EXPERIENCE	84.2	159.7	0	826.0
1/NUM COMPETING PROJECTS	.14	.07	.07	.33
HISTORICAL MARKET POWER	26.9	34.5	1.0	100.0
ALIGNER RESOLUTION	2.77	3.22	.80	15.0
DIVERSIFIED FIRM	.55	.50	0	1.0
INCUMBENT	.61	.49	0	1.0
RADICAL	.45	.50	0	1.0
CONTACT	.18	.39	0	1.0
PROXIMITY	.10	.31	0	1.0
STEP AND REPEAT, FIRST GENERATION	.31	.47	0	1.0
STEP AND REPEAT, SECOND GENERATION	.20	.41	0	1.0

References

ABERNATHY, W.J. *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry.* Baltimore: Johns Hopkins University, 1978.

ACS, Z.J. AND AUDRETSCH, D.B. "Innovation in Large and Small Firms: An Empirical Analysis." *American Economic Review,* Vol. 78 (1988), pp. 678–690.

ARROW, K.J. "Economic Welfare and the Allocation of Resources for Inventions." In R. Nelson, ed., *The Rate and Direction of Inventive Activity: Economic and Social Factors.* Princeton, N.J.: Princeton University Press, 1962.

———. *The Limits of Organization.* New York: Norton, 1974.

BALDWIN, W.L. AND SCOTT, J.T. *Market Structure and Technological Change.* New York: Harwood Academic Publishers, 1987.

BRAUN, E. *Revolution in Miniature: The History and Impact of Semiconductor Electronics.* Cambridge: Cambridge University Press, 1978.

BRESNAHAN, T.F. "Post-Entry Competition in the Plain Paper Copier Market." *American Economic Review,* Vol. 75 (1985), pp. 15–19.

BURNS, T. AND STALKER, G.M. *The Management of Innovation.* 2d ed. London: Tavistock, 1966.

CHANDLER, A.D. *Strategy and Structure.* Cambridge, Mass.: MIT Press, 1962.

———. *Scale and Scope.* Cambridge, Mass.: Harvard University Press, 1990.

CLARK, K.B. "Managing Technology in International Competition: The Case of Product Development in Response to Foreign Entry." In A.M. Spence and H.A. Hazard, eds., *International Competitiveness.* Cambridge: Ballinger, 1988.

——— AND FUJIMOTO, T. *The Management of New Product Development: The Case of the World Automobile Industry.* Cambridge, Mass.: Harvard Business School Press, 1992.

COHEN, W.M. AND LEVIN, R.C. "Empirical Studies of Innovation and Market Structure." In R. Schmalensee and R.D. Willig, eds. *Handbook of Industrial Organization.* New York: North-Holland, 1989.

CYERT, R.M. AND MARCH, J.G. *A Behavioral Theory of the Firm.* Englewood Cliffs, N.J.: Prentice-Hall, 1963.

DAFT, R.L. "Bureaucratic versus Nonbureaucratic Structure and the Process of Innovation and Change." *Research in the Sociology of Organizations,* Vol. 1 (1982), pp. 129-166.

DEWAR, R.D. AND DUTTON, J.E. "The Adoption of Radical and Incremental Innovations: An Empirical Analysis." *Management Science,* Vol. 32 (1986), pp. 1422-1433.

ENOS, J.L. *Petroleum Progress and Profits: A History of Process Innovation.* Cambridge, Mass.: MIT Press, 1962.

ERICSON, R. AND PAKES, A. "An Alternative Theory of Firm and Industry Dynamics." Working paper no. 445, Columbia University, Department of Economics, 1989.

ETTLIE, J.E., BRIDGES, W.P. AND O'KEEFE, R.D. "Organization Strategy and Structural Differences for Radical versus Incremental Innovation." *Management Science,* Vol. 30 (1984), pp. 682-695.

FREEMAN, C. *The Economics of Industrial Innovation,* 2d ed., Cambridge, Mass.: MIT Press, 1982.

GALBRAITH, J.R. *Designing Complex Organizations.* Reading, Mass.: Addison-Wesley, 1973.

GILBERT, R.J. AND NEWBERRY, D.M. "Preemptive Patenting and the Persistence of Monopoly." *American Economic Review,* Vol. 72 (1982), pp. 514-526.

——— AND ———. "Uncertain Innovation and the Persistence of Monopoly: Comment." *American Economic Review,* Vol. 74 (1984a), pp. 238-242.

——— AND ———. "Preemptive Patenting and the Persistence of Monopoly: Reply." *American Economic Review,* Vol. 74 (1984b), pp. 251-253.

GRILICHES, Z. (ed.): *R&D, Patents and Productivity.* Chicago: University of Chicago Press, 1984.

HANNAN, M.T., AND FREEMAN, J. "Structural Inertia and Organizational Change." *American Sociological Review,* Vol. 49 (1984), pp. 149-164.

HEDBERG, B. "How Organizations Learn and Unlearn." In P.C. Nystrom and W.H. Starbuck, eds., *Handbook of Organizational Design.* New York: Oxford University Press, 1981.

HENDERSON, R. "The Failure of Established Firms in the Face of Technical Change: A Study of Photolithographic Alignment Equipment." Ph.D. Dissertation, Department of Economics and Harvard Graduate School of Business, Harvard University, 1988.

——— AND CLARK, K.B. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms." *Administrative Science Quarterly,* Vol. 35 (1990), pp. 9-30.

HOLLANDER, S. *The Sources of Increased Efficiency: A Study of Du Pont Rayon Plants.* Cambridge, Mass.: MIT Press, 1965.

JOVANOVIC, B. "Selection and the Evolution of Industry." *Econometrica,* Vol. 50 (1982), pp. 649-670.

MINITZBERG, H. *The Structuring of Organizations.* Englewood Cliffs, N.J.: Prentice-Hall, 1979.

MOCH, M.K. AND MORSE, E.V. "Size, Centralization and Organizational Adoption of Innovations." *American Sociological Review,* Vol. 42 (1977), pp. 716-725.

MOWERY, D.C. AND ROSENBERG, N. *Technology and the Pursuit of Economic Growth.* Cambridge, England: Cambridge University Press, 1989.

NELSON, R.R. AND WINTER, S.G. *An Evolutionary Theory of Economic Change.* Cambridge, Mass.: Harvard University Press, 1982.

PAVITT, K., ROBSON, M., AND TOWNSEND, J. "The Size Distribution of Innovative Firms in the UK.: 1945-1983." *Journal of Industrial Economics,* Vol. 35 (1987), pp. 297-316.

REINGANUM, J.F. "Uncertain Innovation and the Persistence of Monopoly." *American Economic Review,* Vol. 73 (1983), pp. 741-748.

———. "Uncertain Innovation and the Persistence of Monopoly: Reply." *American Economic Review,* Vol. 74 (1984), pp. 243-245.

———. "The Timing of Innovation: Research, Development and Diffusion." In R. Schmalensee and R.D. Willig, eds., *Handbook of Industrial Organization.* New York: North-Holland, 1989.

SALANT, S.W. "Preemptive Patenting and the Persistence of Monopoly: Comment." *American Economic Review,* Vol. 74 (1984), pp. 247-250.

SCHUMPETER, J.A. *The Theory of Economic Development.* Cambridge, Mass.: Harvard University Press, 1934.

———. *Capitalism, Socialism and Democracy.* 3d ed. New York: Harper, 1950.

SIMON, H.A. "A Behavioral Model of Rational Choice." *Quarterly Journal of Economics,* Vol. 69 (1955), pp. 99-118.

———. "Theories of Decision-Making in Economics and Behavioral Science." *American Economic Review,* Vol. 49 (1959), pp. 253-283.

TUSHMAN, M.L. AND ANDERSON, P. "Technological Discontinuities and Organizational Environments." *Administrative Science Quarterly,* Vol. 31 (1986), pp. 439-465.