The R&D Boundaries of the Firm: An Empirical Analysis

Gary P. Pisano
Harvard University

This paper examines how two sources of transaction costs, small-numbers-bargaining hazards and appropriability concerns, may affect established firms' choices between in-house and external sources of R&D when technological change shifts the locus of R&D expertise from established enterprises to new entrants, and established firms face a make-or-buy decision for R&D projects. The relationships of other organizational characteristics to the R&D procurement decision are also considered. Hypotheses are tested with data on 92 biotechnology R&D projects that major pharmaceutical companies have sponsored either in-house or through external contractual arrangements. The results suggest that small-numbers-bargaining problems motivate firms to internalize R&D. Evidence is also found that a firm's R&D experience, its dependence on the pharmaceutical business, and its national origin affect R&D procurement decisions.•

The ability of firms to develop and exploit technological know-how is an important dimension of competition in many industries. Firms' internal research and development (R&D) capabilities are often viewed as the critical determinant of such abilities. However, while in-house R&D has traditionally been an important source of technical know-how for firms (Mowery, 1983), it is not the only possible source. Firms can tap the R&D capabilities of competitors, suppliers, and other organizations through such contractual arrangements as licenses, R&D agreements, and joint ventures. Various empirical studies have documented significant interfirm, interindustry, and intertemporal differences in the degree to which firms obtain R&D services from in-house versus external sources (e.g., von Hippel, 1982; Bozeman and Link, 1983; Pavitt, 1986).

R&D procurement decisions become particularly relevant for established enterprises confronting broad and rapid changes in their core technologies. During such gusts of "creative destruction" (Schumpeter, 1975: 83), established firms' in-house laboratories may lack the relevant technological skills to perform R&D competitively with new entrants. Decisions about which new technical capacities to develop internally and which ones to access through collaborative and contractual links with external sources may affect the firm's long-term viability in the new technological environment. For example, electronics firms that decided in the early 1960s to license-in the new integrated circuit technologies rather than to develop the requisite R&D capabilities in-house had difficulty competing for many years afterward (Malerba, 1985).

Many factors may affect a firm's choice between internal (hierarchical) and contractual (market) modes for organizing a product R&D program. This paper examines the role that transaction costs may play in make-versus-buy decisions for product R&D. While transaction-cost theory has been used in empirical analyses of production and supply activities (Monteverde and Teece, 1982a, 1982b; Stuckey, 1983; Masten, 1984; Walker and Weber, 1984; Balakrishnan and Wernerfelt, 1986; Joskow, 1987) as well as marketing (Anderson and Schmittlein, 1984), its application to the study of the R&D boundaries of the firm has been limited. Williamson (1975),

0001-8392/90/3501-0153/$1.00.

•

The author would like to thank Glenn Carroll, Robert Harris, Michael Katz, Kaz Mishina, Jeffrey Perloff, David Teece, Oliver Williamson, Richard Nelson, Michael Tushman, and the anonymous reviewers for their helpful comments on earlier drafts of this paper. This paper draws from the author's doctoral research, which was supported in part by the National Science Foundation, grant #SRS-841056. Additional support from the Harvard Business School Division of Research is also gratefully acknowledged.

Teece and Armour (1977), and Teece (1988) have argued that R&D is more efficiently governed by hierarchies than by markets. However, the various propositions about the best organizational location for R&D have never been tested with project-level data. This situation stands in contrast to transaction-cost analyses of make-or-buy decisions for production, which have used data at the level of individual components and subassemblies (Monteverde and Teece, 1982a; Masten, 1984; Walker and Weber, 1984).

This paper develops and tests transaction-cost hypotheses for R&D procurement at the project level. While there are many potential sources of transaction costs, including engineering intensity and design specialization (Monteverde and Teece, 1982a, 1982b; Masten, 1984), technological uncertainty (Walker and Weber, 1984; Balakrishnan and Wernerfelt, 1986), and the co-location of specialized assets (Joskow, 1987), this analysis focuses on the following two: (1) small-numbers-bargaining hazards stemming from specialized R&D capabilities and (2) appropriability problems arising from competition in product markets.

Small-numbers-bargaining hazards play a central role in the transaction-cost theory of the firm. However, theoretical and empirical analysis of their effects has been largely confined to intermediate product markets. Whether small-numbers-bargaining hazards also influence R&D markets is a question that remains to be answered. The question is important, because transaction-cost theory must be applicable to R&D as well as production activities if it is to be considered a robust theory of the firm. Appropriability problems have always been an issue of central concern in the economics of innovation (Schumpeter, 1975; Arrow, 1962). More recently, Teece (1986, 1988) argued that appropriability problems are a critical factor impeding market contracting for R&D. Despite its salience, little empirical research has been done on the causes of appropriability problems and their consequences for the organization of R&D.

The empirical analysis in this paper examines the decisions of established pharmaceutical companies to develop new biotechnology-based pharmaceutical products through in-house R&D versus through contractual arrangements with outside firms. The case of biotechnology is particularly interesting because it represents a relatively dramatic change in the technological environment of established pharmaceutical firms. It thus provides an opportunity to examine how transaction costs and other factors may affect the way established firms adjust their R&D boundaries in the wake of such changes.

The biotechnology industry has been the context of other studies on the organization of innovation. Shan (1989) examined the organizational modes through which start-up firms in the biotechnology industry have chosen to commercialize their technologies. While his study and the present one draw data from some of the same sources, they differ in fundamental ways. Shan's analysis focused on how a new firm's competitive position affects its decision whether to commercialize its technologies on its own or through a cooperative arrangement with a partner. The determinants of cooperative commercialization strategies for these start-up firms was the

central concern of his study. The present study is concerned with the R&D procurement behavior of large, established firms already capable of commercializing the technology. The transactional difficulties of R&D contracts and how these affect established firms' R&D procurement form the conceptual heart of this analysis.

TECHNOLOGICAL CHANGES AND THE BOUNDARIES OF THE FIRM

Episodes of "competence-destroying" technological change (Tushman and Anderson, 1986), which suddenly make existing skills and capabilities obsolete, are often characterized by a shift in the locus of technical expertise from industry incumbents to newly formed ventures and firms from other industries. Competition from these new entrants and their eventual triumph over established firms is what Schumpeter (1975: 83) had in mind when he referred to the process of "creative destruction." However, a competitive clash between new entrants and incumbents is not an inevitable outcome of such technological upheavals. In some cases, technological change that weakens or destroys established firms' advantages in R&D and production has little or no effect on their relative advantage in distribution and marketing. Such "revolutionary" technological change (Abernathy and Clark, 1985) generates differences in distinctive competences. The new entrants capture a relative advantage in R&D while the established enterprises maintain their advantage in commercializing products. This situation creates opportunities for beneficial trade, rather than competition, between the new sources of technical expertise and the established firms.

The emergence of biotechnology during the late 1970s is an example of a revolutionary technological change (in Abernathy and Clark's sense) for the pharmaceutical industry. Basic research in molecular biology during the 1970s yielded a number of discoveries about how the genetic structure of cells could be manipulated to induce them to produce specific proteins. These discoveries created a methodology for synthesizing potential therapeutic proteins that were too complex to be synthesized through the chemical methods traditionally used in pharmaceutical research. As a means of synthesizing therapeutic compounds, biotechnology represented a competence-destroying technology because it required technical skills that were fundamentally different from those with which established pharmaceutical firms were familiar. For this reason, most of the early commercial biotechnology R&D was conducted by new ventures that formed in the United States between 1976 and 1982 and not by the established pharmaceutical firms (Office of Technology Assessment, 1984).

While biotechnology was competence destroying on the R&D end, it was competence preserving at the commercialization end. The potential new protein drugs made possible by biotechnology must all go through the same clinical tests and regulatory approval process and are sold through the same distribution channels as traditional drugs. With years of commercial experience and existing organizational capabilities in these "downstream" functions, established pharmaceutical companies had an advantage over new entrants in bringing new drugs from the laboratory to the market.

An established pharmaceutical firm that wanted to commercialize a biotechnology-based pharmaceutical product faced the following choice: develop the required R&D capabilities in-house (vertically integrate) or procure the necessary R&D services from a new biotechnology firm. Vertically integrating (on any given project) would mean forgoing the opportunity to tap the distinctive R&D competence of a new biotechnology firm. Because new biotechnology firms could do R&D in this technology more effectively than an inexperienced in-house team, external R&D procurement would seem to be a more economically rational alternative. Because it was difficult for the new firms to commercialize their own products, they might find it equally attractive to collaborate with established enterprises.

In light of these apparent economies of functional or vertical specialization, the incidence with which established pharmaceutical companies undertook biotechnology R&D projects internally is striking. The data presented in this paper suggest that, as of 1986, established pharmaceutical firms were conducting slightly less than half (47 percent) of their biotechnology R&D projects in-house. This paper examines some of the factors that have affected the extent and direction of backward integration into biotechnology R&D by individual pharmaceutical companies and, specifically, how transaction costs may have impeded markets for biotechnology R&D.

Transaction-Cost Theory

As an economic approach to organization, transaction-cost theory attempts to explain why institutional structures other than markets are necessary for the efficient governance of economic activity. It assumes that, due to economies of specialization and the administrative and incentive limits of hierarchies (Williamson, 1985; Grossman and Hart, 1986), markets are a more efficient governance structure, unless a transaction is surrounded by special circumstances. What these special circumstances are, how they arise, and what implications they have for institutional design have been the focus of research in transaction-cost economics over the past fifteen years (e.g., Williamson, 1975, 1985; Klein, Crawford, and Alchian, 1978; Teece, 1982). Transaction-cost theory posits that the costs of market (contractual) governance increase when the terms of exchange are surrounded by uncertainty and require a party to invest in transaction-specific assets. Uncertainty over the terms of trade arises when the contingencies affecting the execution of the agreement are complex and difficult for the trading partners to understand, predict, or articulate. Contracts made under such conditions are necessarily incomplete and may require renegotiation when unexpected contingencies occur. Renegotiation, however, represents a hazardous proposition for a party that has limited exchange alternatives. This situation, known as the small-numbers-bargaining problem (Williamson, 1975), can occur when a firm invests in assets that are costly to transfer to alternative transactions or uses. Because such transaction-specific assets limit the firm's ability to switch partners, they make it vulnerable to opportunistic recontracting.

The hazards of repeatedly entering into contractual agreements that involve uncertainty and transaction-specific assets

provide an incentive for vertical integration. Internalization eliminates the ex post bargaining problems that might arise with an outside partner and thus improves incentives to commit specialized capital. Of course, internalization should only take place if the governance economies exceed the incremental economic costs due to additional administrative burdens, incentive distortions, and losses in production efficiency that occur when a firm's in-house capabilities are inferior to those of outside sources (Williamson, 1985; Grossman and Hart, 1986).

Transaction-cost theory can help us to understand R&D boundary choices that occur in the wake of technological changes that make existing R&D capabilities obsolete but preserve capabilities needed to commercialize the new technology. As such, they create opportunities for trade between firms that are masters of the new R&D field and those that continue to be strong in commercial functions. Transaction-cost theory can help us understand why firms may vertically integrate despite the benefits of trading with external parties.

Transaction Costs in Markets for Biotechnology R&D

Uncertainty pervades the process of discovering, synthesizing, and formulating a therapeutic compound through biotechnology R&D. At the outset of a project, accurate assessments of costs, duration, and outcomes are virtually impossible. The uncertainties of R&D in general can only be resolved sequentially as the project progresses (Nelson and Winter, 1977). As a result, parties to an R&D contract usually recognize that it is futile to attempt to lock-in the terms of trade at the outset. Instead, they generally agree to renegotiate the contract as uncertainties are resolved and unexpected contingencies arise. The following passage from an actual R&D agreement between Agricultural Genetic Sciences (AGS) and AC Biotechnics is typical:

> It is anticipated by the parties that the program will require adaptation to actual development. Consequently, the parties intend currently to review experiences gained during the program implementation and to agree on all significant needs for adjustment of the program. . . . (contract disclosed in exhibit to AGS's 1984 10-K Report)

Due to the need to adapt sequentially, parties to an R&D agreement can expect repeated rounds of negotiation during a single project. Because a biotechnology R&D project may run for several years, it is more characteristic of a long-term recurrent transaction than a one-shot exchange. Transaction-cost theory is relevant here because it recognizes that start-up costs of vertical integration make it desirable only for recurring transactions and not for one-time exchanges. Such recurrent transactions within the biotechnology industry are hypothesized to involve two types of contractual hazards that may lead to vertical integration: (1) small-numbers bargaining and (2) appropriability problems.

Small-numbers bargaining. At various stages in the project, the sponsor (a pharmaceutical company) and its R&D partner (usually a new biotechnology firm) must renegotiate such contractual terms as reimbursement of R&D costs, distribution of property rights, and completion dates. The contractor is usually reimbursed for its R&D costs, plus some margin of

profit when the project reaches specific "milestones." Biotechnology R&D projects are costly, and the difficulty of reviewing the progress of the project very frequently means that the sponsor has generally invested significant amounts in a project by the time renegotiation occurs. Whether such investments are transaction-specific and allow the R&D supplier to bargain opportunistically depends on the sponsor's options for transferring the project to an alternative supplier.

In R&D agreements, the sponsor is generally entitled to whatever technology had been developed with its funds up to the point of contract termination. The technology is usually "delivered" in the form of molecules, cells, experimental data, models, and other written descriptions. However, such media cannot capture the tacit dimensions of the relevant technological know-how (Teece, 1976). Transferring a project from one R&D partner to another will therefore involve some losses in progress because the new partner will not have access to all of the tacit knowledge gained by the original R&D team during the project. However, the magnitude of these losses will depend on whether the new R&D partner has some experience or capabilities in the same product application area.

Codified descriptions and other technological artifacts provide more valuable insights to an experienced firm than to a novice firm about how the technology was developed and what future paths might be fruitful. The project's progress will be impeded much more if the project is transferred to a supplier who lacks experience and must start the project from the beginning. Thus, if a sponsor has alternative suppliers with relevant R&D experience, it can better preserve the value of its original R&D investment in the event that the agreement with the initial contractor is terminated. If the sponsor cannot find alternative partners with experience, the R&D funding provided to the original contractor is a transaction-specific investment. It has much less value if the project is not completed by the original contractor.

In the procurement of biotechnology R&D, a pharmaceutical company's ability to find alternative partners during a project depends on the degree to which the know-how being procured is specialized to the supplier. Some product areas are more specialized in the sense that the relevant R&D capabilities are concentrated within a relatively small group of suppliers. The accumulation of expertise and proprietary know-how impedes the entry of other suppliers into the same product R&D area. For R&D in a relatively specialized product area, a pharmaceutical company that contracts with an outside supplier has limited options should the supplier bargain opportunistically during one of the renegotiation cycles. Because the sponsor could not credibly threaten to switch partners, it would be stuck in a small-numbers-bargaining situation, which itself creates an incentive for the R&D supplier to bargain opportunistically.

The small-numbers-bargaining problem can also extend into future projects. Once a technological paradigm is established, one generation of product development provides the starting point for subsequent efforts (Nelson and Winter, 1977; Dosi, 1982; Tushman and Anderson, 1986). The firms that have

R&D expertise in one generation of product development are likely to become the experts in the next. If a pharmaceutical company contracts out for R&D capabilities that are relatively specialized to a small group of R&D suppliers, it may have difficulty finding or switching partners for future projects aimed at the same product application area. Under these circumstances, investments in durable assets that are specialized to the product market (such as distribution capabilities or reputation) are a source of "quasi-rents" (Monteverde and Teece, 1982b) and leave the pharmaceutical company vulnerable to rent extraction in negotiating agreements for future projects.[1]

When alternative partners are available, partner switching is a credible action because R&D contracts generally allow the sponsor to retain or share with the contractor the rights to the technology. In addition, the sponsor generally gets to keep (or share with the contractor) technical data, materials, and other descriptive artifacts that were generated in the course of the contract. As noted earlier, these provide a valuable starting point for an experienced supplier. Thus, the key factor limiting the sponsor's ability to switch partners is the availability of alternative partners with relevant experience.

The above discussion suggests that the costs of market governance for a biotechnology R&D project are related to the number of R&D suppliers with R&D programs in the same product application area. In markets where R&D capabilities are specialized to a few suppliers, procurement of R&D through contracts involves small-numbers-bargaining problems. These hazards provide an incentive for internalization. This leads to the following hypothesis:

Hypothesis 1: A pharmaceutical company will be more likely to internalize R&D in those biotechnology product areas in which R&D capabilities are concentrated in fewer R&D suppliers.

Appropriability problems. Firms invest in R&D (both internal and external) to generate and gain proprietary access to specific products and to the more general know-how related to those products. For example, an R&D project that yields a specific therapeutic compound may also create knowledge and build R&D capabilities that are valuable for discovering other drugs for the same disease. The firm not only has an interest in gaining access to both the specific and more general know-how, but also in restricting rivals from using it.

When a project is done internally, the R&D organization can be prohibited (by fiat) from transferring know-how to competitors. When the project is sponsored externally, however, the restriction must be incorporated into the contractual agreement. Such restrictions require a clear delineation of the relevant property rights and a mechanism for enforcing those rights. The sponsor must be able to claim ownership of specific technologies and, by virtue of its ownership, restrict the contractor's right to transfer them to third parties.

An obvious problem arises in specifying all the relevant intellectual property rights. While it may be possible to identify specific elements (such as a particular molecule), much of the broader, applications-level know-how and R&D capabilities that are generated cannot be clearly defined or adequately described in a contract. The know-how generated from one

1

Quasi-rents are the difference between an asset's value in its first-best use and its value in its next-highest value use. Pharmaceutical companies often spend heavily on promoting a new drug and establishing a recognized brand name in the product area. The difference between these assets' value in their use for one product versus their next-best use for another product represents quasi-rents.

project may be so inextricably linked with that created in other projects that it may be impossible to agree on who owns what. As a result, the sponsor is unable to attach claims to much of the valuable intellectual property that is created during the R&D project. Even when specific intellectual property rights claims can be negotiated, enforcement may be problematic, given the uncertain scope and efficacy of biotechnology patents (Cooper, 1987).

An inability either to define or enforce intellectual property rights creates a hazard of expropriation. The R&D contractor may be able to sell the know-how arising from the project to the sponsor's product-market rivals. One of the determinants of the expropriation hazard is the number of rivals with an interest in commercializing applications of the technology. While new biotechnology firms often do not work on the exact same product with more than one commercial sponsor, they commonly work on R&D projects in the same therapeutic application for different clients. Each rival competing in the same therapeutic market represents a possible buyer for such technology in either current or future generations of product competition. Thus, highly competitive therapeutic markets provide an incentive for the pharmaceutical firm to internalize the development of technology. This leads to the second hypothesis:

Hypothesis 2: A pharmaceutical company will be more likely to internalize R&D in those biotechnology product markets in which it faces greater competition from other established pharmaceutical companies.

Other Factors Affecting R&D Procurement Decisions

Going back to Coase (1937), a fundamental axiom of transaction-cost economics is that the boundaries of the firm are determined by the trade-off between the transaction costs of using the market and the organizational costs of using hierarchies. Organizational costs within the economics literature have typically included those factors that make the firm less efficient at either performing or governing certain activities internally. If firms act rationally, they will adjust their boundaries when the trade-off between transaction costs and internal organizational costs change. However, behavioral theories of the firm (e.g., Simon, 1955; Cyert and March, 1963; Nelson and Winter, 1982) posit that bounded rationality prevents firms from making optimal adjustments to environmental changes. These theories suggest that there are internal organizational factors that affect the way firms decide to adjust their organizational boundaries. Incorporating into the model these behavioral factors, as well as those factors affecting the costs of internalizing R&D, will help isolate the effects of transaction costs on R&D boundary choices. The factors discussed below represent the set for which adequate data were available.

Historical factors. A firm's historical pattern of R&D procurement should affect its R&D procurement decisions in the new technological regime in two ways. First, according to a behavioral perspective of the firm, historical patterns of R&D procurement reflect deeply engrained repertoires (Simon, 1947), search rules (Cyert and March, 1963), operating procedures (Allison, 1971), and routines (Nelson and Winter, 1982).

These organizational elements affect how firms perceive changes in the environment, the menu of possible responses they consider, and the choices they ultimately make. According to a behavioral perspective, "firms may be expected to behave in the future according to the routines they have employed in the past" (Nelson and Winter, 1982: 134). Thus, we would expect that routines underlying a historical pattern of internal R&D will lead the firm to internalize R&D even when technology changes.

The second way historical R&D procurement patterns affect current R&D procurement decisions is through their effect on the relative organizational costs of using either markets or hierarchies for R&D. Firms lacking experience with R&D contracting are likely to be less able to search for and select R&D partners and to absorb technologies from external sources (Westney, 1986). Due to their inexperience, these firms may be more vulnerable to the contractual hazards discussed earlier or at least perceive a greater degree of risk. As a result, for any given level of external factors affecting transaction costs, a firm inexperienced with purchasing technology from outside sources is more likely to find internalization a more attractive option. The above discussion suggests the following hypothesis:

Hypothesis 3: A pharmaceutical firm that tended to use in-house R&D for its traditional pharmaceutical products will have a greater propensity to internalize R&D for biotechnology-based products.

R&D experience in the relevant technology. Previous research on technological innovation suggests that when technical advance is cumulative (e.g., Nelson and Winter, 1977) a firm's efficiency in performing a particular type of R&D project depends on its prior experience with similar R&D projects. An R&D "learning curve" results, because the know-how needed to innovate at time $t + 1$ depends on what is learned in the course of R&D at time t. Therefore, a firm's ability to internalize new projects may depend on the number of its previous in-house projects in the relevant technology. A firm that has begun biotechnology R&D relatively early will have accumulated skills and experience that would reduce the costs of undertaking subsequent projects internally. In terms of Coase's (1937) original formulation of the problem, this R&D experience reduces the costs of internalizing new R&D projects; holding transaction costs constant, it should increase the likelihood of internalization:

Hypothesis 4: A pharmaceutical firm will be more likely to undertake a biotechnology R&D project in-house when it has accumulated more in-house R&D experience in the relevant area of biotechnology.

Focus. Decisions to expand the R&D boundaries of the firm into a new technological field are generally made at the highest levels of the corporation. Even when a pharmaceutical company is a division of a diversified corporation, corporate-level management normally plays an important role in allocating the additional resources required for expanding its R&D boundaries. Corporate management will be more likely to approve of internalization when it views the emerging technology as strategically important to the corporation. Many factors are likely to affect whether a technology is labeled as strategically important. One factor is the size of the pharmaceutical business relative to other businesses managed by

the corporation. Where pharmaceuticals account for a small share of an enterprise's total activities, the relative impact of biopharmaceuticals on the enterprise may be small. As a result, corporate management is likely to focus its scarce attention (Simon, 1978) and corporate resources on the other lines of business. In contrast, biopharmaceutical technologies are more likely to be viewed as strategically important (to corporate management, which allocates the necessary resources) as pharmaceuticals become a greater share of the corporation's total business activities. This leads to the following hypothesis:

Hypothesis 5: A firm with a higher percentage of its business in pharmaceuticals will be more likely to internalize biotechnology-pharmaceutical R&D projects.

Firm size. Previous research suggests that firm size affects organizational behavior (Scherer, 1980; Miles, 1980) in general and organizational boundary decisions in particular. Anderson and Schmittlein (1984) found that in the electronics industry, the likelihood that a firm will use an internal sales force (rather than independent representatives) increases with firm size. Theoretically, the effect of firm size on R&D boundaries is unclear. On one hand, when expanding R&D boundaries involves fixed costs (such as new equipment and laboratory facilities), larger firms may have scale-economy advantages. They also have more resources to invest in the development of internal capabilities. On the other hand, because increasing size adds complexity to the administrative process, size can have a negative effect on R&D performance. Transaction-cost theorists, beginning with Coase, have generally identified decreasing returns to scale in administration as one of the limiting factors of vertical scope. Empirical work by Clark, Chew, and Fujimoto (1987) suggested that firms can reduce the complexity of managing projects and improve project performance by using suppliers for some development tasks.

National origin. A firm's national-geographic origin may influence its R&D boundary choices by affecting its relative costs of undertaking R&D. When, as in the case of biotechnology, there are national-regional differences in technological expertise, firms from one country may find it more costly to pursue R&D themselves than to purchase R&D from firms in another country better endowed with the relevant personnel and scientific expertise. To control for these effects, a set of national origin dummies was included in the model tested in this study.

METHOD

Sample. To test the hypotheses presented above, data were gathered on R&D project-level procurement decisions of pharmaceutical companies. To provide a starting point for the search, a list of the world's top 50 pharmaceutical companies in 1982 was obtained from *Scrip World Pharmaceutical News* (December 20, 1982: 23). The ranking was based on the total number of new pharmaceutical products a firm had in development in 1982; this number included new products originating from both internal and external R&D sources. Of the 50 firms on this initial list, 43 were also ranked in the world's top 50 by sales.

The largest pharmaceutical firms in the world are an appropriate sampling frame for the analysis because these firms all have established positions in pharmaceutical markets. Because I was interested in modeling backward vertical integration from marketing to R&D, I needed to confine my observations to firms with established commercial positions. I also needed to observe firms that had at least some interest in commercializing biotechnology-based products. As one descends the ranks of pharmaceutical firms, there is a much lower probability that either criterion (commercial position or interest in commercializing biotechnology products) would be met. Preliminary sample selection also indicated that the information needed for the relevant independent and dependent variables would be very difficult to obtain for firms below the top 50. Between them, the 50 firms on the initial list accounted for 53 percent of all of the world's pharmaceutical products in development in 1982 (*Scrip,* December 20, 1982: 23). Thus, while these 50 firms represented a small share of the total number of pharmaceutical firms worldwide, they accounted for a very significant share of the world's total efforts to commercialize new pharmaceutical products.

The next task was to generate a sample of pharmaceutical biotechnology R&D projects in which these 50 firms were involved, either alone or in collaboration with an external source of technology. Two main data sources were used for this purpose: (1) Paine Webber's 1986 *Biotechnology Fact Book* and (2) a data base compiled by a California biotechnology firm. The latter data base was provided to the author under conditions of confidentiality. However, the data contained in it are drawn from public primary sources (annual reports, the industry trade press, industry newsletters, etc.). Thus, data used in this analysis are reproducible. This data base contained information on the R&D and commercial activities of over 700 firms throughout the world that are involved in biotechnology. Both data sources contained information on whether a particular firm was doing a specific R&D project alone or in collaboration with an external partner. For purposes of the analysis, R&D was defined as the activities needed to synthesize, formulate, and test a pharmaceutical product prior to human clinical trials. Thus, the sample did not include projects that had already progressed to the first phase of human clinical trials.

Projects that had progressed to clinical trials and beyond were not included in the sample because it was difficult to obtain consistent and verifiable data on whether a pharmaceutical company obtained a particular product technology through an R&D contract or a technology licensing agreement. R&D contracts and technology licensing agreements are fundamentally different transactions. In an R&D contract, a sponsoring firm is funding an R&D project undertaken by its partner. As discussed earlier, it is a relatively long-term transaction that involves significant contractual uncertainties. Technology licensing agreements are more characteristic of one-time exchanges in which the rights to an already-developed technology are transferred from one firm to another. In the pharmaceutical industry, technology licensing agreements are often struck when the product is ready to begin clinical trials. Therefore, many of the biotechnology products in clinical trials

and beyond could have been obtained through technology licensing agreements and not R&D contracts. Because the hypotheses developed above explicitly concerned R&D arrangements, it was necessary to limit the sample to R&D projects.

Additional verification was provided by examining the 10-K reports of newly formed biotechnology firms. These documents commonly discuss the firm's contracts and joint ventures. It was therefore possible to use them to verify particular collaborations between new biotechnology firms and established firms from the sample.

This procedure uncovered a total 94 R&D projects across 30 of the sample firms. However, for two projects, there were no new biotechnology firms working in the relevant area of product R&D. Because external procurement of R&D would be almost impossible in these cases (it would be a "no-numbers" bargaining situation), their inclusion in the sample would bias the results in favor of hypothesis 1. They were therefore excluded, and the final sample consisted of 92 cases. Although precise information on timing was not available, it is presumed that most of these projects began after 1982. Because of the time frame of the data bases, none could have begun after 1986.

The sample of projects could hardly be considered homogenous. Undoubtedly, the projects differed in terms of costs, riskiness, technological uncertainty, degree of difficulty, and other dimensions. Unfortunately, such project characteristics are generally considered by firms to be highly proprietary and thus the relevant data were not available. The degree of unmeasurable heterogeneity, however, is limited by the sampling procedure. All of the projects were in roughly the same technological stage of development; all were based on the same basic technologies and scientific principles; all were for pharmaceutical products; and all had met some minimum threshold for potential technological and commercial viability. Table 1 lists the pharmaceutical firms and their R&D projects in the final sample.

The dependent variable. The column on the far right of Table 1 represents the dependent variable in the analysis, the *i*th pharmaceutical firm's choice of undertaking the *j*th R&D project through in-house or collaborative modes. It was coded as follows: $M_{ij} = 1$ if the *i*th pharmaceutical firm's R&D on the *j*th project was completely internal; or $M_{ij} = 0$ if the *i*th pharmaceutical firm's R&D on the *j*th project involved an external source.

In 47 percent of the cases in the sample, the pharmaceutical firm was doing the R&D project internally (i.e., without an external partner). It should be noted that in most of the cases involving an external source, the partner was a new biotechnology firm. My research and discussions with industry personnel suggest that in these cases, R&D is almost always the sole responsibility of the new biotechnology firm partner. Thus, the dependent variable corresponds very well to the dichotomy between internal and external R&D. For the few cases involving two established firms, the proprietary data base mentioned above was consulted to determine the primary R&D supplier. In the five cases in which there was evi-

Table 1

The Sample of R&D Projects

Case	Firm	Project (Main Application)	In-house R&D (yes/no)
1.	Hoffman La Roche	Interleukin-1 (cancer)	yes
2.	Hoffman La Roche	Immunoagents (cancer)	no
3.	Hoffman La Roche	Herpes II vaccine (herpes II)	yes
4.	Hoffman La Roche	Anti-inflammatory protein (immune modifier)	yes
5.	Bristol-Myers	Alpha-Interferon (immune modifier)	no
6.	Bristol-Myers	Beta-Interferon (immune modifier)	no
7.	Bristol-Myers	Gamma-Interferon (immune modifier)	yes
8.	Bristol-Myers	Immunotoxin (cancer)	yes
9.	Bristol-Myers	Cartilage Inducing Factor (bone growth)	no
10.	Hoechst	Burst Promoting Activity (immune modifier)	no
11.	Hoechst	Colony Stimulating Factor (CSF) (immune modifier)	no
12.	Hoechst	CSF-granulocyte (immune modifier)	no
13.	Hoechst	CSF-1 (immune modifier)	no
14.	Hoechst	Beta-Interferon (immune modifier)	yes
15.	Hoechst	Interleukin-2 (immune modifier)	yes
16.	Hoechst	Hemopoeitin (anemia)	no
17.	Hoechst	Tissue Plasminogen Activase (tPA) (blood clot dissolving)	no
18.	Hoechst	Human Growth Hormone (hGh) (growth regulator)	yes
19.	Merck	Gamma-Interferon (immune modifier)	yes
20.	Merck	Interleukin-1 (Beta) (immune modifier)	yes
21.	Merck	Somatostatin Analog (growth regulator)	yes
22.	Merck	Herpes II vaccine (herpes II)	yes
23.	American Home Products	Renin Inhibitor (hypertension)	no
24.	Upjohn	Interleukin-1 (Beta) (immune modifier)	yes
25.	Upjohn	Albumin (blood plasma)	yes
26.	Upjohn	Protein C (blood coagulation regulator)	yes
27.	Upjohn	Renin Inhibitor (hypertension)	yes
28.	Upjohn	tPA (blood clot dissolving)	yes
29.	Upjohn	Atrial Natriuretic Factor (ANF) (hypertension)	yes
30.	Johnson & Johnson	Interleukin-2 (immune modifier)	no
31.	Johnson & Johnson	Factor VIII-C (blood clotting)	no
32.	Eli Lilly	Immunoagent (cancer)	no
33.	Eli Lilly	Immunocytotoxic agent (cancer)	no
34.	Eli Lilly	Protein C (blood clot regulator)	yes
35.	Eli Lilly	Gram-Negative MAb (gram negative infections)	yes
36.	Ciba Geigy	Alpha-Interferon (immune modifier)	no
37.	Ciba Geigy	Gamma-Interferon (immune modifier)	no
38.	Ciba Geigy	Renin Inhibitor (hypertension)	yes
39.	Ciba Geigy	tPA (blood clot dissolving)	no
40.	Ciba Geigy	Somatomedin C (growth regulator)	no
41.	Sandoz	GM-Colony Stimulating Factor (immune modifier)	no
42.	Sandoz	Alpha-Interferon (immune modifier)	yes
43.	Sandoz	Pro-urokinase (blood clot dissolving)	no
44.	Boehringer Ingelheim	Beta-Interferon (immune modifier)	no
45.	Rhone Poulenc	Immunotoxin agent (organ transplants)	no
46.	Rhone Poulenc	Factor IX (hemophaelia)	no
47.	Bayer	Factor VIII-C (hemophaelia)	no
48.	Bayer	Pseudomonas MAb (septic shock)	no
49.	Schering-Plough	CSF (immune modifier)	yes
50.	Schering-Plough	CSF-other (immune modifier)	yes
51.	Schering-Plough	IgE Peptide (allergies)	yes
52.	Schering-Plough	Beta-Interferon (immune modifier)	no
53.	Schering-Plough	Interleukin-4 (immune modifier)	yes
54.	Schering-Plough	Erythropoietin (EPO) (anemia)	no
55.	Meiji Seika	Beta-Interferon (immune modifier)	no
56.	Takeda	IgE Peptide (allergies)	yes
57.	Takeda	Immunoagent (cancer)	no
58.	Smithkline	IL-1 Antagonist (cancer)	yes
59.	Smithkline	Alpha-1-Antitrypsin (emphysema)	yes
60.	Smithkline	tPA (blood clot dissolving)	no
61.	Pfizer	Renin Inhibitor (hypertension)	yes
62.	Pfizer	ANF (hypertension)	yes
63.	Syntex	Interleukin-1 (Beta) (immune modifier)	no
64.	Syntex	Immunotoxin (cancer)	yes

(continued on next page)

Table 1

The Sample of R&D Projects *(continued)*

Case	Firm	Project (Main Application)	In-house R&D (yes/no)
65.	Schering AG	Somatostatin (growth regulator)	yes
66.	Wellcome	Gamma-Interferon (immune modifier)	yes
67.	Wellcome	tPA (blood clot dissolving)	no
68.	Wellcome	Malaria vaccine (malaria)	yes
69.	Kyowa Hakko	Alpha-Interferon (immune modifier)	yes
70.	Kyowa Hakko	Immunotoxin (cancer)	no
71.	Fujisawa	Tumor Necrosis Factor (Beta) (cancer)	no
72.	Fujisawa	tPA (blood clot dissolving)	no
73.	Fujisawa	Renin Inhibitor (hypertension)	yes
74.	Sankyo	Macrophage Activating Factor (immune modifier)	no
75.	Sankyo	Tumor Necrosis Factor-Alpha (cancer)	no
76.	Sankyo	tPA (blood clot dissolving)	no
77.	Sankyo	ANF (hypertension)	no
78.	Sankyo	Calcitonin (bone diseases)	no
79.	Sanofi (Elf)	tPA (blood clot dissolving)	yes
80.	Sanofi (Elf)	hGH (growth regulator)	yes
81.	Sanofi (Elf)	Somatomedin C (growth regulator)	yes
82.	American Cyanamid	Immunoagent (cancer)	no
83.	American Cyanamid	Immunocytotoxic agent (cancer)	no
84.	American Cyanamid	Herpes II vaccine (herpes II)	no
85.	Green Cross	CSF-1 (immune modifier)	no
86.	Green Cross	Albumin (blood plasma)	no
87.	Green Cross	tPA (blood clot dissolving)	yes
88.	ICI	Alpha-Interferon (immune modifier)	yes
89.	Yamanouchi	Anti-Inflammatory Protein (immune modifier)	no
90.	Yamanouchi	tPA (blood clot dissolving)	no
91.	G. D. Searle	Beta-Interferon (immune modifier)	no
92.	G. D. Searle	Renin Inhibitor (hypertension)	yes

dence that both firms were contributing R&D, the case was treated as external/collaborative ($M_{ij} = 0$).[2]

The independent variables. Hypothesis 1 concerns the effect of small-numbers-bargaining conditions in the supply of R&D services. As noted above, new biotechnology firms are the overwhelmingly dominant source of external biotechnology R&D for established firms. Thus, for each project, the number of new biotechnology firms with R&D programs in the same therapeutic application was used to measure the extent to which small-numbers-bargaining conditions were present. Information on the therapeutic application of each product under development was available in Paine Webber's 1986 *Biotechnology Fact Book.* Data on the number of new biotechnology firms ($SUPPLIERS_j$) working in each of these therapeutic markets were available from the same source. The therapeutic application of each project is shown in Table 1 in parentheses after the product name or type.

A therapeutic area of application is broader than a specific project area. Multiple products can be aimed at a given therapeutic application (e.g., cancer treatment). Constructing the variable at this level allows for the possibility of substituting R&D sources within a class of therapeutically similar products. For example, if a collaborative project for a specific cancer drug terminates, it is not necessary for the sponsor to find another partner working on the exact same product. An R&D contractor with other cancer product projects would presumably be more willing and able to pick up the unfinished

2

An odd number of these cases is possible because the partners are not included in the sample.

project than one outside of the cancer area. The fact that a new biotechnology firm is working on projects within a therapeutic area means that it has "disease-specific" know-how. Thus, taking on the project would not require it to build up biomedical expertise in a new field.

In the model developed here, the variable $SUPPLIERS_j$ is specified in log form because an increase in the number of suppliers in an R&D market does not always have the same effect on small-numbers-bargaining hazards. For example, if there is only one new biotechnology firm supplying R&D services in a particular area of therapeutic application, a significant small-numbers-bargaining hazard exists. This hazard is much lower if there is an alternative supplier. A third supplier will further decrease the potential hazards, although its effect will be less than having only the second supplier in the market. In contrast, small-numbers-bargaining problems are almost nonexistent in an R&D market with 20 suppliers: an additional supplier in this market does little to reduce the already trivial small-numbers-bargaining hazards.

Hypothesis 2 concerns the effects of product-market rivalry among established pharmaceutical companies. For each project, the number of established pharmaceutical companies (i.e., all firms except new biotechnology firms) attempting to develop or commercialize the same product or other products within the same area of therapeutic application was used to measure rivalry. New biotechnology firms were not counted as being rivals in the commercialization stage because they have generally lacked the capabilities to commercialize products on their own. As of 1989, only one new biotechnology firm (Genentech) has commercialized a human therapeutic biotechnology product (tissue plasminogen activase) on its own; however, that firm uses partners to market the product outside of the United States. The measure of rivalry was aggregated over the entire world market. This world aggregation was viewed as appropriate in light of the increasing globalization of pharmaceutical product competition among the world's first-tier pharmaceutical companies (Thomas, 1988). This measure was also constructed from information in the Paine Webber report.

A logic similar to that explained above for the SUPPLIERS variable also justifies the use of a log specification for the RIVALS variable. An additional firm in a relatively concentrated market represents a major change in the number of rivals and, presumably, the intensity of competition. An additional rival in an already crowded market, however, may be barely noticeable.

To measure the historical propensity of each firm in the sample to obtain product R&D from its own laboratories (versus external sources), the following ratio was used:

$$HISTORY_i = \frac{\text{Number of Own R\&D products in development (1982)}}{\text{All R\&D products in development (1982)}}$$

where "Own R&D products" refers to pharmaceutical products in development that originated from the firm's own R&D laboratories and "All R&D products" refers to the total number of pharmaceutical products (from both internal and

external sources) the firm had in development. The difference between the numerator and the denominator is the number of products in development contracted from external sources. The year 1982 was chosen because it is far enough in the past not to include a significant number of biotechnology R&D projects. It thus avoids simultaneity with the dependent variable. Because of the long research and development cycles associated with pharmaceuticals, this construct picks up the effects of decisions made over the previous five-to-seven-year period. A firm with a HISTORY variable closer to 1 has tended to be more vertically integrated into traditional (non-biotechnological) pharmaceutical R&D. According to hypothesis 3, we would expect such procurement behavior to carry over into the procurement of biotechnology R&D. Data on the number of own R&D pharmaceutical products and total number of pharmaceutical products under development in 1982 were available from *Scrip* (December 20, 1982).

To test hypothesis 4, it was necessary to construct a variable that would measure a firm's biotechnology R&D experience in the technological area in which each project was conducted. Because the sample contained only ongoing R&D projects, the number of completed projects could be taken as an indicator of each firm's accumulated experience in biotechnology R&D. These prior in-house projects were identified as follows. Using the data sources described earlier, it was possible to generate a list of biotechnology products for each firm that were, as of 1986, either in clinical development, awaiting regulatory approval, or already on the market. These same data sources could also be used to determine whether a specific product originated from in-house R&D or an external source. Through this method, it was possible to generate a list of biotechnology R&D projects that each firm had completed on its own, without an external partner.

Using information in the Paine Webber report, each project was classified into one of the following six technological categories: (1) immune modifiers, (2) anticancer agents, (3) blood proteins and enzymes, (4) hormones, (5) anti-infectives, or (6) vaccines. The effects of prior experience are hypothesized to be relatively specific within categories of technology. To capture these category-specific effects, a variable (BIO-EXPERIENCE$_{ij}$) was created that equaled the number of completed R&D projects by firm i in biotechnology category J. J would vary across projects in the sample. For example, if an observation corresponded to Bristol-Myers' choice of developing an anticancer product in-house (versus externally), the independent variable would take on a value that reflected the number of previous in-house anticancer biotechnology projects undertaken by Bristol-Myers.

To test hypothesis 5, data were gathered from annual reports on the percentage of each firm's total sales attributable to its pharmaceutical business. Data for the Japanese firms were drawn from *The Japan Company Handbook* (Tokyo: Toyo Keizai Shinposha) for the years 1982–1985. The variable was termed FOCUS$_i$.

Firm size was measured in terms of pharmaceutical sales. Pharmaceutical sales was used instead of total corporate sales because economies and diseconomies of internal orga-

nization should occur at the business unit (or divisional) level rather than at the corporate level. Data on sales were available from annual reports and *The Japan Company Handbook*. A quadratic specification for the SALES variable was used to allow for the possibility that the direction of the effect may change with the size of the firm. Because theory does not provide unambiguous prior expectations, however, three other specifications are shown: SALES only, log(SALES), and no size variable at all.

To capture the effects of national origin, firms in the sample were classified geographically as (1) American-based, (2) European-based, or (3) Japanese-based. In the model, dummies on European-based and Japanese-based firms were included.

Descriptive statistics. Table 2 lists the frequency with which the therapeutic applications appear in the sample. Table 3 presents the means, standard deviations, minimums, and maximums of the independent variables. Frequencies are presented for the dependent variable, the national origin dummies, and BIO-EXPERIENCE$_{ij}$.

Table 2

Frequency of Therapeutic Applications

Therapeutic Application	Cases
1. Immune system modifiers	31
2. Cancer	14
3. Blood clot dissolving	11
4. Hypertension	9
5. Growth regulators	6
6. Vaccine for herpes II	3
7. Anemia	2
8. Blood plasma	2
9. Blood clotting (surgical applications)	2
10. Blood clotting (hemophaelia)	2
11. Allergies	2
12. Bone growth	1
13. Bone diseases	1
14. Blood coagulation regulators	1
15. Gram-negative infections	1
16. Organ transplant rejection	1
17. Septic shock	1
18. Emphysema	1
19. Vaccine for malaria	1

The relative inexperience of established pharmaceutical companies with in-house biotechnology R&D is apparent. In most cases, the pharmaceutical firms had no in-house R&D experience in the relevant technological category. The maximum experience any firm had in any one major class of biotechnologies was two prior R&D projects. Although this appears to be a small number of R&D projects, pharmaceutical R&D projects typically take from one to five years (before clinical trials) and can cost several million dollars (Schwartzman, 1976). Thus, a firm that had already completed two R&D projects in a particular area of biotechnology would have accumulated significant technical experience.

Table 4 presents the correlations among the continuous independent variables. There is a very high correlation between

Table 3

Means, Minimums, Maximums, and Standard Deviations of the Variables

Variable	Mean	S.D.	Min.	Max.
$SUPPLIERS_i$	19.14	13.08	1	35
Log ($SUPPLIERS_i$)	2.58	1.001	0	3.5
$RIVALS_i$	27.64	17.65	2	49
Log ($RIVALS_i$)	2.99	.95	.69	3.9
$HISTORY_i$	.77	.11	.48	.89
$BIO\text{-}EXPERIENCE_{ij}$	.26	.57	0	2
$FOCUS_i$	49.24	23.16	7.0	95.0
$SALES_i$ ($ in thousands)	1251	596	333	2452

Frequencies

	Number of Cases per Category of Discrete Variables			
Variable	0	1	2	Total
M_{ij}	49	43	N/A	92
EUROPEAN FIRM	58	34	N/A	92
JAPANESE FIRM	74	18	N/A	92
AMERICAN FIRM	52	40	N/A	92
$BIO\text{-}EXPERIENCE_{ij}$	74	12	6	92

the independent variables log($SUPPLIERS_i$) and log($RIVALS_i$). This positive correlation should make it more difficult to get significant estimates on the corresponding parameters (which are hypothesized to have opposite signs).

Table 4

Correlations among Continuous Independent Variables ($N = 92$)

Variable	1	2	3	4	5	6
1. Log ($SUPPLIERS_i$)						
2. Log ($RIVALS_i$)	.92					
3. $HISTORY_i$	−.11	−.16				
4. $FOCUS_i$	−.11	−.03	−.03			
5. $SALES_i$	−.009	−.04	.10	−.50		
6. $SALES_i^2$	.009	−.02	.06	−.47	.98	
7. Log ($SALES_i$)	−.03	−.07	.17	−.49	.96	.89

The low correlation between the share of a firm's total sales from pharmaceuticals and its historical propensity to procure R&D from in-house (versus external) sources is noteworthy in light of hypothesis 5. Hypothesis 5 postulates that firms with a greater share of their sales from pharmaceuticals will be more likely to internalize R&D in new pharmaceutical technologies. The low correlation mentioned above suggests that the link between the firm's share of sales from pharmaceuticals and its tendency to procure R&D internally does not hold historically.

Analysis. Probit was used to estimate the effects of the independent variables on the probability of doing R&D internally. A probit model assumes that the underlying probabilities follow a cumulative normal distribution. Except at its tails, this distribution is similar to the cumulative logistic function used in a logit model (Amemiya, 1979: 1487; Maddala, 1983: 23). However, to ensure the results were not

sensitive to the probability distribution chosen, a logit model was also estimated. No differences in signs or levels of statistical significance resulted. Only the probit results are shown here. The model is specified in the following form:[3]

$$P(M_{ij} = 1) = F[a_0 + B_1\log(\text{SUPPLIERS}_j) + B_2\log(\text{RIVALS}_j) + B_3\text{HISTORY}_i + B_4\text{BIO-EXPERIENCE}_{ij} + B_5\text{FOCUS}_i + B_6\text{SALES}_i + B_7\text{SALES}_i^2 + B_8(\text{NATIONAL ORIGIN DUMMIES}) + e_{ij}],$$

where $P(M_{ij} = 1)$ is the probability that pharmaceutical firm i will undertake R&D project j in-house, and $F[.]$ is the cumulative normal distribution. As noted above, three alternative specifications of size were also estimated.

RESULTS AND DISCUSSION

The probit estimates are presented in Table 5. They support the transaction-cost hypothesis that a more concentrated supply side of the R&D market increases the likelihood of internalization. The hypothesis that rivalry in the therapeutic market would also lead to internalization (due to potential appropriability problems) was not supported at statistically significant levels. Despite the high correlation between these two variables, there was statistically significant evidence that at least one type of transactional hazard (small-numbers bargaining) affects R&D procurement decisions.[4]

The effect of a firm's historical propensity to procure R&D internally on its R&D procurement decisions was not statistically significant. Thus, the results do not suggest a strong history effect. One possible interpretation is that biotechnology created a significant enough break with past methods to dilute the effects of historical capabilities and traditional behavioral patterns. The costs of internalizing new biotechnology capabilities may have forced firms with traditionally high internal procurement biases to procure a relatively greater share of their biotechnology R&D needs outside the firm.

The effect of biotechnology R&D experience was positive, in the expected direction. These results show that there is an association between R&D procurement decisions at one time and prior R&D experience in the relevant technical area. Such a result suggests that the accumulation of specific technical capabilities may be an important determinant of a firm's incremental R&D boundary decisions. A longitudinal analysis is required to explore these dynamic effects in more detail.

The effect of a firm's dependence on the pharmaceutical business was significant and positive, in the expected direction. Companies more dependent on pharmaceutical sales seemed to be more likely to internalize biotechnology R&D projects. As noted previously, the relationship between a company's dependence on pharmaceutical sales and its tendency to procure traditional (chemical-based) pharmaceutical R&D internally does not seem to hold historically (see Table 4, correlation = −.03). That is, firms with a relatively high percentage of their sales in pharmaceuticals did not, historically, develop a higher proportion of their traditional pharmaceutical products through in-house R&D. The results of the probit analysis indicate, however, that firms with a relatively high

[3] The inclusion of technological category dummies was suggested to me in the review process. In a pretest of the model, however, the set of technological category dummies was not statistically significant; there are therefore no statistical grounds for their inclusion.

[4] The effect of log(SUPPLIERS$_j$) is also robust. When the model is run without the log(RIVALS$_j$) variable, the coefficient on log(SUPPLIERS$_j$) remains negative and statistically significant. See column 5 of Table 5.

Table 5

Parameter Estimates for the Probit Model*

Variables	Model (1)	(2)	(3)	(4)	(5)
CONSTANT	−.432	.221	2.982	−.563	.568
	(1.653)	(1.405)	(3.168)	(1.275)	(1.331)
Log (SUPPLIERS$_i$)	−.962•	−.953•	−.944•	−.860•	−.459••
	(.427)	(.424)	(.424)	(.411)	(.160)
Log (RIVALS$_i$)	.566	.552	.545	.505	
	(.436)	(.430)	(.430)	(.427)	
HISTORY$_i$	.705	.760	.826	.731	.577
	(1.401)	(1.402)	(1.407)	(1.393)	(1.365)
BIO-EXPERIENCE$_{ij}$	.762•	.687•	.632•	.534•	.687•
	(.320)	(.300)	(.286)	(.271)	(.296)
FOCUS$_i$	.017•	.017•	.017•	.019•	.018•
	(.008)	(.008)	(.008)	(.008)	(.008)
SALES$_i$	.64E-03	−.47E-03			−.42E-03
	(.002)	(.0003)			(.0003)
SALES$_i^2$	−.41E-06				
	(.56E-06)				
Log (SALES$_i$)			−.483		
			(.395)		
EUROPE$_{(dummy)}$	−.262	−.281	−.296	−.320	−.258
	(.364)	(.363)	(.361)	(.358)	(.360)
JAPAN$_{(dummy)}$	−1.885••	−2.046••	−2.108••	−1.734••	−1.965••
	(.595)	(.585)	(.595)	(.490)	(.539)
Log-likelihood	−48.812	−49.083	−49.234	−50.003	−49.931
Chi-square	29.52•••	28.98•••	28.68•••	27.14•••	27.29•••
% Cases predicted correctly	74	75	74	73	75

• $p < .05$; •• $p < .01$; ••• $p < .001$.
* Standard errors are in parentheses.

percentage of their sales in pharmaceuticals have a proportionally higher likelihood of developing new biotechnology pharmaceutical products through in-house R&D. One plausible hypothesis is that a radical change in the core technology of a particular line of business (pharmaceuticals) alters firms' perceptions about the strategic importance of technology. Of course, confirmation of this hypothesis would require analysis of the product and supplier markets of the nonbiotechnology R&D projects as well as other factors included in the present model.

The signs of the SALES and SALES^2 variables in equation 1 were in the expected direction (positive for SALES and negative for SALES^2). However, the individual coefficients were not statistically significant. A log-likelihood ratio test indicated that the coefficients on SALES and SALES^2 were not jointly significant. The log-likelihood ratio test statistic is $Z = -2(LL_1 - LL_2)$, where LL_1 is the log of likelihood function for the constrained model (equation 4, $LL_1 = -50.003$) and LL_2 is the log of the likelihood function for the unconstrained model (equation 1, $LL_2 = -48.812$). Since Z is a distributed chi-square with degrees of freedom equal to the number of restrictions, the critical value is 5.99 ($p < .05$). Since in this case, $Z = 2.382$, the coefficients are not jointly significant. The size effects were not statistically significant in either the SALES-only specification or the log(SALES) specification. Exclusion of the size effects, however, had little effect on the estimates of the other parameters in the model (equation 4).

The data thus do not provide evidence that firm size affects decisions whether or not to internalize new R&D programs.

A log-likelihood ratio test indicated that the national origin dummies were significant. The log of the likelihood function of the unconstrained model (equation 1) was −48.812. If the two national origin dummies are constrained to be 0 (i.e., eliminated from the model), the log of the likelihood becomes −54.22. Since $-2(-54.22 + 48.812) = 10.82$, and the critical value of a chi-square distribution with 2 degrees of freedom is 5.99, we can reject the null hypothesis: national origin does appear to affect firms' decisions whether to undertake R&D in-house or procure it through contractual arrangements. As discussed earlier, various national-regional differences in "endowments" of indigenous biotechnology know-how may be responsible for these effects. To the extent that size creates different advantages and liabilities in different national and regional contexts, there may also be interactions between national origin and size variables, although such interactions were not significant in any pretests of the model in this study. A study of specific international differences might clarify these results.

Only the sign and level of statistical significance of the parameters can be interpreted directly from probit estimates. Unlike linear regression, probit coefficients do not have a direct interpretation. The effect of a change in independent variable X_k on the probability of internalizing the project can be represented as follows:

$$dP/dX_k = B_k\, f(XB),$$

where B_k = the estimated coefficient on variable k, and $f(XB)$ is the value of the normal density function at the point XB. This formula translates the estimated coefficients into a more intuitive number. It can be evaluated at any point (or several points) in the distribution.

The instantaneous rate of change in the probability of internalization will always be greatest at the mean of a cumulative normal distribution. Evaluating the instantaneous rate of change at the mean therefore indicates just how strong the hypothesized effect may be. This formula shows that a very small change in log(SUPPLIERS) from its mean will change the probability of internalization by a factor of .37. This suggests that in the region (around the mean) where they are strongest, small-numbers-bargaining effects can be substantively significant.

CONCLUSION

Technological change can affect organizations and the environment in which they compete in many different ways. In some cases, technological change shifts the locus of R&D expertise from established enterprises to new entrants. Previous research has suggested that such episodes of technological change result in a competitive struggle between an industry's new and incumbent firms (Schumpeter, 1975; Abernathy and Clark, 1985; Tushman and Anderson, 1986). Established firms are presumed to be able to resist the gusts of "creative destruction" only by adopting the new R&D and production skills required to compete with the new entrants. However, an alternative response for established firms is to

procure some R&D projects from external sources and to focus internal resources on those functions such as marketing, in which they have a distinctive advantage.

This paper posited that transaction-cost factors influence whether an established firm would attempt to expand its R&D boundaries into a particular subfield of the new technology or procure the relevant capabilities from an outside source. The hypothesis that small-numbers-bargaining hazards in R&D markets motivate internalization of R&D was supported by the data. The other hypothesis, that rivalry among established firms would lead to internalization, was not supported. The data also suggest that firm-level factors (R&D experience, dependence on the industry affected by the technological change, and location) influence R&D procurement patterns. However, a firm's procurement patterns in the old technological regime did not seem to affect its procurement behavior in the new technology. Size was also not a significant factor.

By providing insights about the factors influencing R&D boundaries of established firms, this study can help us to better understand how the structure of competition between new entrants and established firms may evolve in the wake of technological change. Conditions that make R&D contracting hazardous can be expected to create competition rather than cooperation between new entrants and established firms. In this environment, the success of new firms will depend on their ability to build capabilities in such commercial activities as marketing and distribution; the survival of established firms will depend on their ability to acquire and develop new R&D skills. A different structure, one involving cooperation between vertically or functionally specialized firms, may evolve when R&D can be efficiently governed by contracts. In this environment, survival may depend much more on a firm's ability to select partners and manage cooperative relationships than on its ability to develop new R&D capabilities.

This study has examined R&D boundary decisions of established firms within a context in which it is reasonable to assume that new R&D-intensive entrants are unlikely to integrate into product markets. As a result, it has been able to address only the transaction costs of buying technology. Future research should examine other contexts, such as biotechnology-based diagnostics, in which new entrants have lower barriers to integration into product markets. This would provide insights about the factors contributing to the transaction costs of selling as well as buying technology. Other potential sources of transaction costs, such as technological uncertainty and the efficacy of patent protection (Levin et al., 1984; Teece, 1986) need to be explored before we have a complete picture of how R&D markets work and how they may influence the organizational environment in the wake of radical technological changes.

REFERENCES

Abernathy, William, and Kim Clark
1985 "Innovation: Mapping the winds of creative destruction." Research Policy, 14: 3–22.

Allison, Graham
1971 The Essence of Decision: Explaining the Cuban Missile Crisis. Boston: Little, Brown.

Amemiya, T.
1979 "Qualitative response models: A survey." Journal of Economic Literature, 19 (December): 1483–1536.

Anderson, Erin, and David Schmittlein
1984 "Integration of the sales force: An empirical examination." Rand Journal of Economics, 15 (3): 385–395.

Arrow, Kenneth
1962 "Economic welfare and the allocation of resources for invention." In Richard Nelson (ed.), The Rate and Direction of Inventive Activity: 609–625. Princeton, NJ: Princeton University Press.

Balakrishnan, Srinivasan, and Birger Wernerfelt
1986 "Technical change, competition and vertical integration." Strategic Management Journal, 7: 347–359.

Bozeman, Barry, and Albert Link
1983 Investments in Technology: Corporate Strategies and Public Policy Alternatives. New York: Praeger.

Clark, Kim, W. Bruce Chew, and Takahiro Fujimoto
1987 "Product development in the world auto industry." Brookings Papers on Economic Activity, 3: 729–771.

Coase, Ronald
1937 "The nature of the firm." Econometrica, 4: 386–405.

Cooper, Ivor
1987 Biotechnology and the Law, 2d ed. New York: Clark Boardman Company.

Cyert, Richard, and James G. March
1963 A Behavioral Theory of the Firm. Englewood Cliffs, NJ: Prentice-Hall.

Dosi, Giovanni
1982 "Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change." Research Policy, 11: 147–162.

Grossman, Sanford, and Oliver Hart
1986 "The costs and benefits of ownership: A theory of vertical and lateral integration." Journal of Political Economy, 94: 691–719.

Joskow, Paul
1987 "Contract duration and relationship-specific investments: Empirical evidence from coal markets." American Economic Review, 77: 168–185.

Klein, Benjamin, Robert Crawford, and Armen Alchian
1978 "Vertical integration, appropriable rents and the competitive contracting process." Journal of Law and Economics, 21 (October): 297–326.

Levin, Richard, Alan Klevorick, Richard Nelson, and Sidney Winter
1984 "Survey research on R&D appropriability and technological opportunity." Unpublished manuscript, Economics Department, Yale University.

Maddala, Gregory
1983 Limited-Dependent and Qualitative Variables in Econometrics. Cambridge: Cambridge University Press.

Malerba, Franco
1985 The Semiconductor Business. London: Frances Pinter.

Masten, Scott
1984 "The organization of production: Evidence from the aerospace industry." Journal of Law and Economics, 27 (October): 403–417.

Miles, Raymond
1980 Macro Organizational Behavior. Santa Monica, CA: Goodyear.

Monteverde, Kirk, and David Teece
1982a "Supplier switching costs and vertical integration." Bell Journal of Economics, 13: 206–213.
1982b "Appropriable rents and quasi-vertical integration." Journal of Law and Economics, 25 (October): 321–328.

Mowery, David
1983 "The relationship between intrafirm and contractual forms of industrial research in American manufacturing, 1900–1940." Explorations in Economic History, 20: 351–374.

Nelson, Richard, and Sidney Winter
1977 "In search of useful theory of innovation." Research Policy, 6 (Summer): 36–76.
1982 An Evolutionary Theory of Economic Change. Cambridge, MA: Harvard University Press.

Office of Technology Assessment, U.S. Congress
1984 Commercial Biotechnology: An International Analysis. Washington, DC: U.S. Government Printing Office.

Pavitt, Keith
1986 " 'Chips' and 'trajectories': How does the semiconductor influence the sources and directions of technical change?" In Roy MacLeod (ed.), Technology and the Human Prospect: Essays in Honour of Christopher Freeman: 31–54. London: Frances Pinter.

Scherer, Frederick
1980 Industrial Structure and Economic Performance. Chicago: Rand McNally.

Schumpeter, Joseph
1975 Capitalism, Socialism, and Democracy, 3rd ed. New York: Harper & Row (Originally published in 1942 by Harper & Brothers).

Schwartzman, David
1976 Innovation in the Pharmaceutical Industry. Baltimore: Johns Hopkins University Press.

Shan, Weijian
1989 "An empirical analysis of organizational strategies by entrepreneurial high technology firms." Working Paper, The Wharton School, University of Pennsylvania.

Simon, Herbert
1947 Administrative Behavior. London: MacMillan.
1955 "A behavioral model of rational choice." Quarterly Journal of Economics, 69: 99–118.
1978 "Rationality as process and as product of thought." American Economic Review, 68 (2): 1–16.

Stuckey, John
1983 Vertical Integration and Joint Ventures in the Aluminum Industry. Cambridge, MA: Harvard University Press.

Teece, David
1976 The Multinational Corporation and the Resource Costs of Technology Transfer. Cambridge, MA: Ballinger.
1982 "Towards an economic theory of the multiproduct firm." Journal of Economic Behavior and Organization, 3: 39–63.
1986 "Profiting from technological innovation: Implications for integration, collaboration, licensing, and public policy." Research Policy, 15: 285–305.
1988 "Technological change and the nature of the firm." In G. Dosi et al. (eds.), Technical Change and Economic Theory: 256–281. London: Frances Pinter.

Teece, David, and Henry Armour
1977 "Innovation and divestiture in the U.S. oil industry." In D. J. Teece (ed.), R&D in Energy: 7–94. Stanford, CA: Stanford University Institute for Energy Studies.

Thomas, Lacey Glenn
1988 "Multifirm strategies in the U.S. pharmaceutical industry." In D. Mowery (ed.), International Collaborative Ventures in U.S. Manufacturing: 147–182. Cambridge, MA: Ballinger.

Tushman, Michael, and Philip Anderson
1986 "Technological discontinuities and organizational environments." Administrative Science Quarterly, 31: 439–465.

von Hippel, Eric
1982 "Appropriability of innovation benefit as a predictor of the source of innovation." Research Policy, 11 (2): 95–115.

Walker, Gordon, and David Weber
1984 "A transaction cost approach to make-or-buy decisions." Administrative Science Quarterly, 29: 373–379.

Westney, D. Eleanor
1986 "Domestic and foreign learning curves in managing international cooperative strategies." Paper presented at "Cooperative Strategies in International Business," colloquium of the Wharton School and Rutgers Graduate School of Management, October 24–26.

Williamson, Oliver
1975 Markets and Hierarchies. New York: Free Press.
1985 The Economic Institutions of Capitalism. New York: Free Press.