Strategic Management Journal
Strat. Mgmt. J., **19**: 1007–1028 (1998)

GOVERNANCE AND UNCERTAINTY: THE TRADE-OFF BETWEEN ADMINISTRATIVE CONTROL AND COMMITMENT

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This study elaborates upon the motives for initiating equity-based collaborations vs. acquisition of another firm already having a desired technology. We characterize both minority direct investments and joint ventures as options to defer either internal development or acquisition of a target firm. In domains where learning about growth opportunities dominates investment activity, this incremental mode of governance economizes on the cost of committing resources to a technology with an uncertain value. Using a sample of 402 transactions in the biotechnology industry, we find strong support for the theoretical model. The findings suggest that the cost of commitment in the face of technological uncertainty may offset the administrative benefits of hierarchical governance. © 1998 John Wiley & Sons, Ltd.

INTRODUCTION

Companies seeking to develop technical capabilities with speed and efficiency often target innovative firms with expertise in research and development (R&D). A central task of firm decision-makers is deciding whether R&D activities should be sourced through collaboration or brought 'in-house' through acquisition. Since R&D activities are often highly proprietary and difficult to transfer across firm boundaries, it has been argued that greater degrees of ownership are required to provide a degree of administrative control for dealing with potentially opportunistic partners (Arrow, 1962; Nelson and Winter, 1977; Williamson, 1985). However, there may be significant costs associated with committing resources to acquire a target firm which may turn out to have little value (Porter, 1980; Harrigan, 1985; Balakrishnan and Koza, 1993). The costs of increased resource commitment may be particularly high in new technical subfields where investment activity is exploratory in nature and revenue streams are distant. We argue that while equity collaborations may sacrifice administrative control relative to acquisition, they also provide a way to economize on the costs of committing to a technology with an uncertain future value.

This study will establish the motives for using equity-based collaborations vs. outright acquisition of a target firm.[1] The equity linkages include both classic joint ventures, where two or more parties create a separate, jointly owned entity; and direct minority investments, where one party takes an equity position of less than 50

Key words: governance; real options; equity collaborations; uncertainty
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[1]Committing immediately to a greenfield investment may be another mode of entry. However, this option is not included in the analysis for two reasons. First, it involves costly and time-consuming R&D and administrative tasks which constrain the speed and efficiency with which development can take place. Thus, the firm may prefer acquisition of a target which already has the technology. Second, from the perspective of this study, the risk characteristics of greenfield investment are the same as those of acquisitions.

CCC 0143–2095/98/111007–22 $17.50

Received 17 April 1995
Final revision received 26 February 1998

percent of its partner. Like Kogut (1988, 1991), Folta (1994), and Hurry, Miller, and Bowman (1992), we view minority investments and joint ventures as efficient modes in which to explore in technical domains that are distantly related. We focus largely on how the governance decision is affected by technological uncertainty—defined as being exogenous to the firm or transaction, and present in industries undergoing technological change (Mitchell, 1988). Equity collaborations are particularly useful when confronted by technological uncertainty because they provide an *option to defer* internal development or acquisition of a target firm or venture. By deferring internalization, the technology buyer can limit its exposure to a technology which may turn out to have little value, and to opportunistic partners who may misrepresent the value of their assets. At the same time, equity collaborations provide a mechanism to capitalize on growth opportunities. Because they grant management the flexibility to adapt its future actions as new information about the technology is revealed, joint ventures and minority investments economize on the cost associated with commitment.

Our work is complementary to the transaction cost literature in that we examine the governance decision in an environment where learning and exploration for new capabilities are paramount. In these domains 'equilibrium contracting' may not fully apply, and transaction cost theory 'should not be applied uncritically' (Williamson, 1991: 293). It is also complementary to a body of work that has recognized the trade-off between commitment and the need for superior administrative control in R&D-intensive industries (Stinchcombe and Heimer, 1985; Balakrishnan and Wernerfelt, 1986; Mody, 1993; Williamson, 1988). Left unexplored is a systematic way to assess the risks of committing to a technology with an uncertain future value, and a framework for evaluating the trade-off between the need for administrative control and the cost of commitment. We use insights from real option theory to illuminate these important issues. Since focus is on the *initiation* of equity collaborations, it is differentiated from Kogut's (1991) work having examined the acquisition of joint venture partners through a real options lens. Figure 1 distinguishes between the initiation decision and the 'exercise' decision.

The next section of the paper elaborates upon the conditions in R&D-intensive industries affecting the need for administrative control and the cost associated with increased resource commitment. We then develop a set of hypotheses and test them with a sample of 402 joint ventures, minority direct investments, and acquisitions in the biotechnology industry from 1984 to 1992, using discrete choice methodology.

BACKGROUND: GOVERNANCE OF R&D

The need for administrative control

While markets are ideal for maintaining incentives to reduce costs and adapt autonomously, the incentives for trading through the market weaken as adaptations require coordinated responses.[2] Asset specificity creates conditions of bilateral dependency, requiring coordinated adaptations.[3] Uncertainty accentuates the frequency with which coordinated adaptations are needed. The fundamental proposition offered by Williamson (1985, 1991) is that governance structures differ in their capacities to confront asset specificity and uncertainty.[4]

Through joint ownership and involvement on boards of directors, equity linkages are thought to contain opportunism and improve monitoring relative to nonequity linkages. However, while a single board of directors may govern the transaction in the event of joint ventures, the presence of two parents may impede effective coordinated adaptations. Cooperation may also suffer in the case of minority investments, particularly when a

[2]Hierarchies distort the incentives of managers in the acquired firm, adding bureaucratic costs (Williamson, 1985; Grossman and Hart, 1986). Williamson (1985) notes that the difficulty of replicating the incentive structures of entrepreneurial firms represents a critical barrier to the acquisition of such firms by large organizations. Not only can divisions of the firm make plausible claims that they are responsible for performance improvements by the division, but divisions that make losses can make plausible claims that others are culpable. Relative to hierarchy, equity collaborations elicit stronger incentives, because they preserve some ownership autonomy and it is more difficult to manipulate accounting systems to share gains or subsidize losses.

[3]Garvey (1993) provided a formal analysis demonstrating how the costs due to haggling rise more rapidly as asset specificity increases than do the costs due to incentive distortions.

[4]It is important to note that Williamson (1991) does not explicitly differentiate between equity and nonequity forms of collaborations, but presents a logic allowing for such a differentiation.

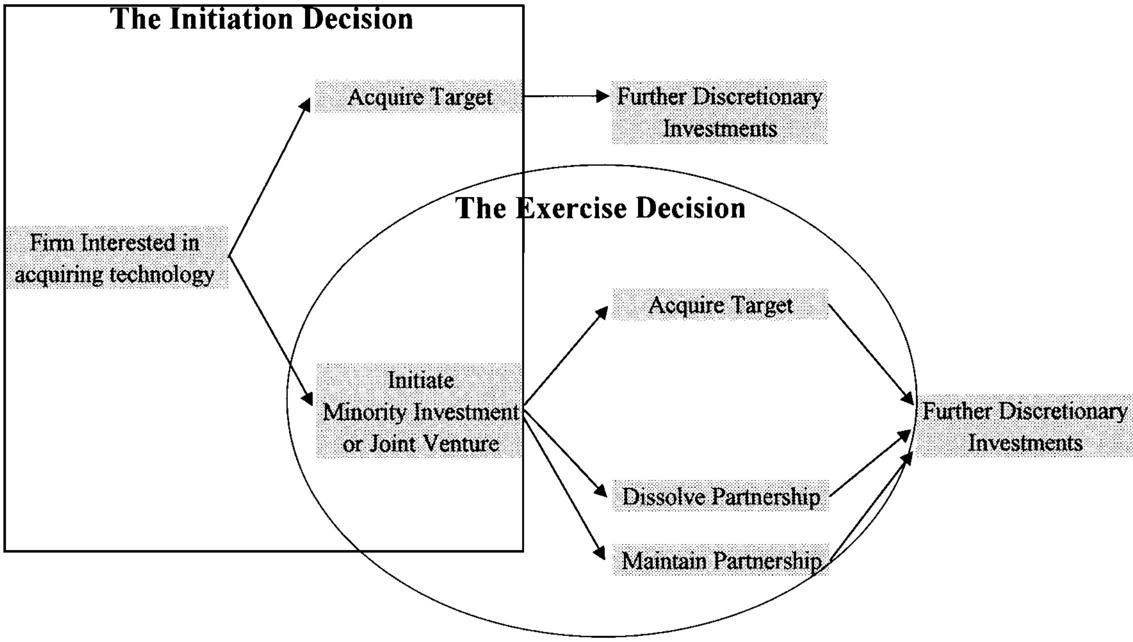

Figure 1. Joint ventures and equity R&D collaborations as a real option

powerful investing firm exhibits self-interested behavior. Because of shared control and a lack of 'unity of command', the administrative costs of managing and controlling equity collaboration may become excessive for transactions involving high levels of asset specificity. These costs are accentuated further when the frequency or variance of environmental disturbances is high, making coordinated adaptation and renegotiation cumbersome, and defection more likely. Hierarchies provide administrative controls suited for adapting to conditions of bilateral dependence, such as monitoring, career rewards, surveillance mechanisms, and penalties. It allows for adaptations to transactions to be made in a sequential way by fiat without the need to consult, complete, or revise interfirm agreements. As a result, cooperation can be achieved where markets and contracts would result in adversarial situations.

It has been argued that greater degrees of R&D investment represent increasing levels of human and dedicated capital specific to a transaction (Armour and Teece, 1980; Caves and Bradburd, 1988; Levy, 1985; Gatignon and Anderson, 1988; Hennart, 1991). The basic line of argument (Arrow, 1962; Williamson, 1985) is that since knowledge is in 'uncodified' form, it is costly to switch to a new relationship, thus exposing firms to opportunistic partners.[5,6] Since R&D transactions in emerging technical industries simultaneously involve a high degree of asset specificity and uncertainty, it is expected that greater degrees of ownership are required to eliminate small-numbers conditions and minimize the threat of opportunism (Arrow, 1962; Williamson, 1985; Pisano, 1989a).

Previous work has demonstrated that when transactions involve R&D activities, there is an increased preference for integration over collaboration (Pisano, 1989a), and a preference for equity collaboration over nonequity collaboration (Pisano, 1989b). Unfortunately, there have been few attempts to empirically distinguish between the relative advantages of equity collaboration and outright acquisition (Pisano, 1989b).[7] Fur-

[5]This argument is distinguished from the organizational learning explanation presented by Kogut (1988), where opportunism is not a necessary condition for hierarchy.

[6]Of course, even though some information is tacit, firms do have the ability to hire away researchers. However, the success with following such a strategy is not known *a priori* and may have a limited effect on the *ex ante* governance decision.

[7]In the international literature there has been some support for the preference of multinational firms to acquire vs. partly acquire foreign subsidiaries in the presence of asset specificity (measured as high R&D expense) (Gatignon and Anderson, 1988; Gomes-Casseres, 1989); although Hennart (1991) found no relationship.

thermore, in contrast to the traditional view cited above, recent empirical studies have noted that joint ventures and minority investments are commonly used in R&D intensive industries (Friar and Horwitch, 1985; Hagedoorn and Schakenraad, 1990; Cainarca, Columbo, and Mariotti, 1992). Why should firms initiate equity collaborations when they could have acquired the target or developed the technology internally?

It is paramount to note that Williamson's prescription—that greater asset specificity and uncertainty accentuate the preference for greater degrees of hierarchy—applies to 'equilibrium' contracting, where transactions occur for mature goods and services (Williamson, 1991). Transacting for R&D in emerging technical subfields introduces two considerations which alter the calculus of the equilibrium prescription. First, firms competing in new technical subfields are largely concerned with developing new capabilities and placing emphasis on learning and experimentation (Madhok, 1997). Second, experimentation in uncertain environments may accentuate the cost of committing immediately to acquisition. Williamson recognized the paradox these considerations presented, relative to the 'equilibrium' prescription:

> A parametric increase in uncertainty . . . can destabilize contracts of the hybrid kind. . . . However, *this is a mature market argument* [emphasis added]. Rather than make specialized investments only to find that costs are greater than or demand for the product is less than anticipated, firms engaged in *developmental work* [emphasis added] will often employ transitional forms of organization. (1988: 360)

We do not mean to suggest that the transaction cost framework has no application to the context of R&D. Indeed, we have cited evidence to the contrary (Pisano, 1989a, 1989b). The central premise of this paper is that while integration may provide superior administrative control of R&D activities, there may be conditions where the benefits associated with acquisition are offset by the opportunity cost of committing aggressively to a technology with an uncertain future value. While the trade-off between commitment and the need for superior administrative control in R&D-intensive industries has been recently addressed by scholars (Stinchcombe and Heimer, 1985; Balakrishnan and Wernerfelt, 1986; Williamson, 1988; Mody, 1993), the conditions where such a trade-off is most prominent have not been elaborated upon. We do so below.

Commitment and the effects of endogenous and exogenous uncertainty

There is a fundamental difference between firms competing in mature industries and firms competing in emerging, knowledge-intensive industries. The market value of the latter is predominantly, if not entirely, based on their option to grow in the future—their ability to develop, search for, and exploit capabilities that they currently do not have (Myers, 1977; Kester, 1984).[8] This stands in contrast to firms competing in more mature industries, where firm value is largely based on the present value of anticipated cash flows.[9] Thus, a key component of firm activity in knowledge-intensive industries is searching for and developing capabilities that are critical for future success (Kogut and Zander, 1992). If such capabilities are known, it may be prudent for the firm to commit to building them as quickly as possible. In this sense, acquisition of a target R&D firm may be viewed as the initiation of an option to grow (Kogut, 1991). However, when there is uncertainty about the capabilities paramount for future competitive advantage, investments in knowledge should have the characteristic of trial-and-error learning. To understand this dynamic, it is necessary to distinguish between endogenous and exogenous uncertainty.

Endogenous uncertainty can be decreased by actions of the firm. It may be due to an inability to assess the value of a target firm, which investments in knowledge will yield products that can be commercialized, or how much time, effort, and materials will be required to complete a project. This kind of uncertainty can only be resolved by learning—actually undertaking the project in stages so that learning can occur incrementally. Projects involving greater degrees of endogenous uncertainty have a wider range of

[8] Miller and Modigliani (1961) initially characterized the market value of a firm as being composed of the present value of cash flows plus the present value of growth opportunities.
[9] March (1991) has made a distinction between 'exploration' for new capabilities and 'exploitation' of existing capabilities. Madhok (1997) argues that 'exploration' is a more critical component of activities than 'exploitation' for firms in dynamic environments characterized by short life cycles and rapid rates of technological change.

potential outcomes, and hence, more growth options. Thus, endogenous uncertainty makes investing more attractive because each stage of investment reveals added information about growth opportunities (Roberts and Weitzman, 1981; Majd and Pindyck, 1987).[10] The key characteristic which makes investment alternatives attractive due to endogenous uncertainty is the ability to temporarily or permanently stop investing if the expected value of the completed project falls due to exogenous shocks. The possibility of stopping midstream makes investment analogous to compound options; each stage completed gives the firm an option to commit additional resources to the opportunity. The greater the endogenous uncertainty, the higher the incentive to invest sequentially.

In contrast to endogenous uncertainty, *exogenous uncertainty is largely unaffected by firm actions*, and is predominantly resolved over time. It is difficult to discern which capabilities are critical for future success when the technological trajectory is not established, or the commercialization potential in the industry is unknown due to the newness of the industry, a lack of industry infrastructure, or important legislation that is pending. Committing prematurely to a technology or to ownership in a target firm may impose considerable risks because the firm gives up the *option of waiting* for new information that might affect the desirability or timing of the investment. The ability to delay an irreversible investment expenditure can be an important source of flexibility in a project and profoundly affect the decision to invest (Cukierman, 1980; McDonald and Siegel, 1986; Pindyck, 1991).[11] Forgoing the option to defer investment creates an opportunity cost that must be included as part of the cost of the investment.

The risks associated with irreversibly investing in a R&D target firm apply with greater force in the case of exogenous uncertainty that is industry or subfield specific, rather than exogenous uncertainty that is firm or project specific (Dixit and Pindyck, 1994). For example, if a biotechnology firm specializing in the human or animal therapeutic subfield fails in an attempt to commercialize a product or to patent a process, it *does not necessarily* imply that the firm's key resources (i.e., its knowledge) cannot be employed productively by another firm. However, if the whole biotechnology industry or therapeutic subfield suffers a negative shock, then the resale value of the target is small and the irreversibility associated with ownership in the target is large. Thus, exogenous uncertainty that is specific to the industry or industry subfield should play the dominant role in influencing the incentive to delay commitment. Similar to Mitchell (1988), we refer to this type of uncertainty as technological uncertainty.

We see then that uncertainty about the value of a project may lead a firm to postpone investing or to speed it up. If the resolution of uncertainty is independent of what the firm does (exogenous or technological uncertainty) there is an incentive to wait. If the uncertainty can be resolved by investing (endogenous uncertainty), it encourages firms to invest, albeit in a sequential way. The latter is crucial in that it suggests the governance decision should not necessarily be evaluated on the efficiency of a single transaction, but rather the comparative efficiency of a sequence of actions. When examining industries where investment is largely exploratory and value is predominantly based on the option to grow in the future, there is added urgency for considering the efficiency of sequential or 'transitional' governance. In the following section we compare the relative advantages and disadvantages of acquisition and equity collaboration for exploring technical subfields.

EQUITY COLLABORATIONS VS. ACQUISITION

Relative to acquisition of a partner, equity collaborations provide a reduced ability to combat opportunistic behavior. At the same time, they involve less economic irreversibility, and hence, less downside exposure in the event of negative shocks to the technological subfield (Teece,

[10]That is why it is often worthwhile to undertake R&D investments even though *ex ante* the NPV of the project is negative (Roberts and Weitzman, 1981).

[11]Investments are irreversible to some degree when they cannot be fully recovered without incurring some costs. Investments in R&D are largely irreversible because they have a high likelihood of being 'bad.' One study (Mansfield *et al*., 1971) based on 16 firms in the chemical, pharmaceutical, petroleum, and electronics industries revealed that only 20 percent of R&D projects resulted in economically successful products or processes. Success rates are likely to be lower in emerging industries, where industry infrastructure is developing and processes are not well established.

1992). Losses are limited to the initial outlay, the equity stake purchased plus the seed money given to the target for research, which is usually much smaller than the funds committed through outright acquisition, the eventual restructuring of unwanted assets (Porter and Fuller, 1987; Nanda and Williamson, 1995), and/or the renegotiation costs of implicit contracts (Jensen, 1993).

In order to manage both forces, administrative control and commitment, we expect firms to employ transitional forms of governance, where equity collaborations precede expansion into a technical subfield through acquisition or internal development. The incidence of transitional governance in technological industries has been supported by Mitchell and Singh (1992), who revealed that 30 percent of firms used joint ventures, minority investments or licensing agreements prior to expanding into new technical subfields. Thus, similar to acquisitions, equity collaborations supply an ability to exploit growth opportunities. At the same time, the investing firm has the flexibility to internalize R&D activities in order to improve administrative control, or to dissolve the partnership at little cost if growth opportunities are minimal. In the following section we argue that equity collaborations will be preferred to acquisition when firms explore in (a) technologically distant domains, (b) technical subfields characterized by high growth potential, (c) the presence of exogenous uncertainty, (d) technical subfields where preemption is less likely.

Technological distance

Like acquisitions, equity collaborations provide the opportunity for learning and gathering new information and experience with the technology and establish a platform for future growth (Kogut and Kulatilaka, 1994). Thus, both provide a mechanism for reducing endogenous uncertainty. The optimal form of governance for coping with endogenous uncertainty should hinge on where learning (or technology transfer) can take place most efficiently and where endogenous uncertainty is greatest.

There is strong theoretical (Kogut and Zander, 1992) and empirical (Kogut and Zander, 1993) evidence which suggests that learning occurs most efficiently inside the organization rather than across organizational boundaries. Relative to equity collaboration, the incremental cost of transferring technology internally is low; especially where the firm already has a strong knowledge base and possesses the routines similar to the acquired firm. At the same time, in distantly related areas endogenous uncertainty is greater. Firms are less adept at learning distantly related capabilities so endogenous uncertainty takes longer to resolve, implying that through acquisition, resources may be committed for prolonged periods before a signal about growth opportunities emerges. Thus, when firms enter unfamiliar areas of activity the marginal efficiency of internalizing the target firm is diminished. Sequential investment does not place the same constraints on firm capabilities. Equity collaborations allow firms to explore multiple opportunities for the cost of a single acquisition. Equity collaborations with a variety of target firms help strengthen and diversify the knowledge base of the firm and provide a more robust platform for developing and strengthening new competencies (Kogut and Zander, 1992; Cohen and Levinthal, 1990). Using this logic, we expect that when exploration occurs in areas distantly related to a firm's existing knowledge base, there will be an increased preference for equity collaborations to acquisition.

A related argument has been made by Balakrishnan and Koza (1993). When a potential acquirer has little information about the true value of the technology, it will be unwilling to commit immediately to acquisition because the target firm may opportunistically misrepresent the value of its assets. The likelihood of the failure of the market for acquisition should be particularly high in R&D-intensive industries because the target's assets are generally tacit and information on asset prices is either costly to obtain or unavailable. As with Akerlof's (1970) problem of adverse selection (the 'lemon's problem'), their argument is premised on the potential for information asymmetry between partners, and thus may be viewed a special case of endogenous uncertainty. Partners whose primary businesses are dissimilar should be most affected by information asymmetry and adverse selection. Similar to our expectation, Balakrishnan and Koza (1993) argue that equity collaborations avoid the problem of adverse selection by providing organizational contact which contributes to learning and gathering information to facilitate the pricing of the target's assets for future acquisition.

In summary, we have argued that investing firms whose knowledge base is similar to target firms will learn most efficiently about growth opportunities through acquisition of the target firm. Where a firm's knowledge base is different from target firms, due to the decreased efficiency of technology transfer inside the firm, capability constraints, and the potential for adverse selection, they will benefit most by equity collaboration because it provides the opportunity to learn about unfamiliar domains or partners in a sequential way. The following hypothesis is offered:

Hypothesis 1: Partners whose primary business operations are dissimilar should prefer equity collaborations over outright acquisition.

Growth potential of technical subfield

Technical subfields may vary in rates of growth and their ability to provide platforms on future growth opportunities. We broadly define this as the subfield's technology value. The greater the technology value the more desirable it is for firms to develop capabilities that can be exploited in the technological subfield. All else being equal, technical subfields with high value should attract more exploratory investment. As argued earlier, exploration is most efficiently enacted in the form of sequential investment. On the other hand, in technical subfields with low value, exploration is less attractive and growth potential should be a smaller component of investment activity. Such low-value environments more closely approximate the equilibrium contracting environment discussed earlier, and should motivate acquisition in order to provide the administrative control necessary for governing R&D activities. As a result, we expect a greater preference for equity collaborations over acquisitions in technical subfields with higher value:

Hypothesis 2: In technical subfields with greater value equity collaboration should be preferred to acquisition.

Technological (exogenous) uncertainty

While endogenous uncertainty should encourage exploration through investment, exogenous uncertainty should create a disincentive to commit, and increase the value of deferring acquisition of the target firm. In the presence of exogenous uncertainty, greater resource commitments involve increased exposure to negative shocks. Relative to equity collaborations, acquisitions are more adversely effected by negative shocks to the technological environment because they involve a greater degree of commitment.

Given positive shocks to the technological subfield, firms having initiated either equity collaborations or acquisitions may be positioned to benefit from growth opportunities, although immediate acquisition may open up potential opportunities that might not persist if commitment was delayed.[12] Furthermore, firms that have committed immediately to acquisition should benefit more because development costs are fixed and will not appreciate with positive shocks to the technology. However, if delayed commitment is not detrimental, equity collaborations provide several means of protecting the investor (hedging) from appreciation of the 'exercise' price. The 'exercise' of the option to defer may take place through internal development or partner buyout.

The ability to take advantage of positive shocks through partner buyouts may reside in the investor's advantageous position in the bargaining for the acquisition of a partner relative to outside buyers (Williamson, 1985; Bulow, Huang, and Klemperer, 1996). In addition, equity collaborations frequently contain rights of residual claimancy, such as 'the right to buy and sell equity' or the 'right of first refusal' (Pisano, 1989b; Chi, 1994). The existence of these rights enables investors to establish a 'preferential link' with the R&D target, and discourages third parties from bidding for the target (Williamson, 1985: 61).[13] If such advantages do not exist, the investing firm has the flexibility to develop the capabilities internally and benefit from positive

[12]Dierickx and Cool (1989) elaborate on the benefits of time compression diseconomies.

[13]An alternative argument is that contractual clauses, such as rights of 'first refusal' or rights of residual claimancy (licensing agreements), may hedge the acquisition price of future equity. For example, by taking an initial equity stake of 3.6 percent in genetic therapy and contributing seed money for R&D, Sandoz gained a right to acquire an additional 32 percent stake at a prespecified price. Even without *ex ante* contractual specification of an exercise price for buying out a partner, transactions involving *ex ante* specification of royalty payments limit the cash flows to the technology supplier to a fixed percentage of sales. Without closer scrutiny, however, it is unclear why these claims are not priced efficiently at the outset of the agreement.

shocks due to relatively fixed development costs, and the possibility for combining new capabilities with existing ones.

Thus, while outright acquisition enables the investing firm to benefit more from positive shocks, it does little to shield it from negative ones. Equity collaborations provide managers the discretion to profitably expand in favorable environments, while avoiding the potential losses associated with acquisition. Thus, equity collaboration provides a distribution of pay-offs better suited for environments with high degrees of technological uncertainty:

Hypothesis 3: Technological uncertainty should lead to a preference for equity collaboration over acquisition.

The risk of preemption

While deferring investment may be valuable, there may be a cost to delaying strategic action, such as the risk of preemption by rivals (Trigeorgis, 1991; Kulatilaka and Perotti, 1995). The risk of preemption by rivals in a technological subfield should decrease the amount of time available for exercising the option to defer internal development or acquisition. While minority investments and joint ventures are sometimes initiated in order to preempt rivals, the degree of protection they provide does not match that provided through acquisition. In acquiring a target firm, the buyer assures access to the subfield, avoids being 'locked-out' by rivals, and inhibits (preempts) rivals from following. As a result, we expect that a greater number of technological rivals will motivate firms to invest aggressively to more quickly resolve endogenous uncertainty and position themselves for growth opportunities:

Hypothesis 4: Fewer rivals in a technological domain are expected to lead to a preference for equity collaboration over acquisition.

Transitional governance or equilibrium contracting?

We have identified the conditions where transitional governance mechanisms are most efficient. These hypotheses are developed with the expectation that there are strong incentives to eventually internalize R&D activities. These incentives may come from the need to efficiently transfer know-how so as to capitalize on valuable growth opportunities (Kogut, 1988), or they may come from the need to provide adequate administrative control for governing R&D transactions (Williamson, 1985). Under these conditions, we have argued that exogenous uncertainty may make the marginal difference in motivating firms to initiate equity collaborations as transitional governance modes. However, there is a reduced need to transition to hierarchy if either of these conditions is relaxed.

For lower degrees of asset specificity there is an increased incentive to initiate equity collaborations as an equilibrium contracting mode because they provide an adequate degree of administrative control. Under such conditions, there is less need to transition to hierarchy so exogenous uncertainty should play little role in dictating a preference for equity collaboration as a transitional mode. As a result, the marginal importance of exogenous uncertainty in domains with low degrees of asset specificity may be low. For these reasons, we expect exogenous uncertainty to have a greater marginal impact on the preference for equity collaborations in domains of higher asset specificity. This expectation stands in contrast to the transaction cost view where it is believed higher uncertainty and greater asset specificity enhance the incentive for hierarchy. We have, however, elaborated upon the need to consider learning and the efficiency of a sequence of actions rather than a single transaction.

Hypothesis 5: The positive impact of technological uncertainty on the preference for equity collaborations over acquisition will be stronger for transactions involving higher degrees of asset specificity.

RESEARCH DESIGN

The context of the empirical examination is the biotechnology industry. Biotechnology is the science and set of techniques for using living organisms—bacteria, yeast, fungi, plant, and animal cells—to produce substances or to perform a commercial purpose. In the private sector, firms dedicated to biotechnology are the dominant source for R&D. There are several reasons why the biotechnology industry is an attractive context for evaluating the costs of committing resources. First, it represents the onset of a new set of technologies with commercial potential that is almost limitless; however, the newness of the industry creates uncertainty regarding the extent of the future value of the technology. Products have proven harder to find than expected, and once found, less easy to develop into marketable propositions. Important gaps in scientific knowledge have caused biotechnology products to reach markets slower than anticipated and R&D costs to generally exceed expectations. Delays and inconsistencies in the issuance of patents *and* the unevenness of the patent playing field have also added to the uncertainties faced by firms in the industry. Also escalating technological uncertainty was the undeveloped regulatory process.

It has been widely recognized that the pace of growth, the promise of a technology, and the uncertainty surrounding its prospects for commercialization vary according to the technical subfield to which it belongs (Dibner, 1992). Biotechnology techniques have applications in a number of subfields, including therapeutic pharmaceuticals, diagnostic pharmaceuticals, agriculture, and chemicals. In this sense, the biotechnology industry is an alternative to a multi-industry study.

Sample

A sample of minority investments, joint ventures, and acquisitions was drawn from the *North Carolina Biotechnology Center* (*NCBC*) *Actions Database*. The *NCBC Actions Database* includes information regarding over 4000 transactions in the biotechnology industry since 1978. The data contain detailed information about collaborative arrangements of firms involved in biotechnology, including the type of transaction, the date of transaction (month), the partners involved, the type of organizations, and the country where transacting organizations are domiciled. The data base also contained information about the relevant product area, or biotechnology subfield. Because four subfields account for a large majority of all the firms dedicated to biotechnology (Dibner, 1992), the sample was limited to the following subfields: Therapeutics, Diagnostics, Ag/Bio, and Suppliers/Specialty Chemical. The sample was further restricted to R&D transactions (excluding production, supply, and marketing agreements) involving a target biotechnology firm domiciled in the United States. Each transaction was verified and supplemented with *BioScan* (Oryx Press, 1992) and the Predicast *F&S Index of Corporate Change*. After deleting miscoded or missing data and transactions involving academic or government agencies, the final sample consisted of 420 transactions.

Dependent variable

The dependent variable identifies the *i*th firm's choice of accessing the *j*th R&D project through minority investment, joint venture, or acquisition. A minority investment is defined as an equity position in a biotechnology firm less than 50 percent, while a joint venture is the formation of a child by two parent firms (one of which is a biotechnology firm). These cases represent 38 percent and 10 percent of the sample transactions, respectively.[14] An acquisition is defined as cumulative ownership of 50 percent or more of a biotechnology firm, essentially giving the investor control of the firm. Acquisitions represent 52 percent of the final sample.

Independent variables

Dissimilar partners

There are basically two types of firms participating in commercial biotechnology: established firms having a core business outside of biotechnology (generally from chemical, pharmaceutical, and agricultural industries), and firms dedicated to biotechnology. The techniques and processes used in biotechnology research differ considerably from the traditional, chemical methods used by large pharmaceutical or chemical companies.

[14] It appears that our sample slightly under-represents the proportion of minority investments and joint ventures relative to samples in previous studies on the biotechnology industry (see Pisano, 1988 and Hagedoorn and Schakenraad, 1990). We should note that since these other samples are also derived from announcements in secondary sources, they are also subject to selectivity bias since the media is more 'aware' of certain governance choices (i.e., acquisitions). Nevertheless, McFadden has shown that if (1) the sample is choice-based, (2) the choice model is multinomial logit, and (3) the choice model has a full set of alternative-specific constants, the maximum likelihood procedure we employ will yield consistent estimates of all parameters except the constants.

While established firms have moved to develop competencies in biotechnology, they still rely on the expertise of biotechnology firms to supplement their operations in biotechnology research. At the same time, biotechnology firms rely heavily on the complementary resources of established firms (marketing expertise, a national or global distribution network, and experience in dealing with regulatory agencies) after the technology has been developed. Since biotechnology and established firms have different areas of expertise, there is an increased likelihood of information asymmetry, and the potential for opportunistic behavior between such firms is greater than when transactions involve firms of like kind. We control for this effect and examine its importance by creating a dummy variable, coded '1' if a biotechnology firm transacted with a large established firm having a core business outside of biotechnology; and coded '0' if the transaction involved two biotechnology firms.

Technology value

In the biotechnology industry, it is widely recognized that the pay-offs to investments vary considerably across technological subfields because of differences in the expected likelihood of commercialization, regulatory requirements, development time horizons, and product demand. To capture the differences in expected value and growth potential across the four subfields (Therapeutics, Diagnostics, Ag/Bio, and Supplier/Specialty Chemical), four stock indices were created from weekly returns of nine U.S. biotechnology firms specializing in the respective subfields. The value of project j's technology was measured as the value of the biotechnology index for subfield m (when $j \in m$) at the announcement of the project. The indices are equally weighted and based on the following formula:

$$I_t = B_0 \frac{A_t}{9} \times \sum_{t=1}^{9} \left(\frac{P_{it}}{P_{i0}} \right) \tag{1}$$

where

I_t = the price level of the index at time t;
B_0 = a base value of the index at $t = 0$, set at 100;
A_t = an adjustment factor which allows for changes in the membership of the index and capitalization changes in companies comprising the index (see Appendix);
P_{it} = the value of stock i at time t; and
P_{i0} = the price of stock i at $t = 0$.

Stock prices were gathered from the Center for Research in Security Prices (CRSP) data base. Index values were created for each week from weekly returns. (P_{it}/P_{i0}). Since the index values will be compared across time, I_t was adjusted for the influence of inflation between October 1983 and time t (see Appendix). These values were then averaged within a month to get a monthly index value. Figure 2 illustrates the relative values of the four (inflation-adjusted) indices for the 452 weeks between October 1983 and December 1992. Most striking is the high value for the Therapeutics subfield, particularly after 1990. Also reflected in this figure is the relative stagnation of the Ag/Bio subfield.

The four indices are meant to represent the distinct promise of each technology subfield. It was important, therefore, to identify a set of firms concentrating primarily in one of the four subfields. Since it is common for many biotechnology firms to be active in more than one subfield, every effort was made to select firms that operated in a relatively narrow technological range, representative of the subfield in which it focused. *BioScan* (Oryx Press, 1992) was used to identify publicly traded firms, their range of research activity, and their stated strategic focus.[15]

Technological uncertainty

Technological uncertainty is meant to capture the exogenous uncertainty specific to the technical subfield. It is calculated from the 26-week standard deviation of the log of (inflation-adjusted) weekly returns for each biotechnology subfield index.[16] Consistent with option pricing models in finance, the following formula was used:

[15] When detail about strategic focus was lacking, a second source was used. The PaineWebber Health Care Group created biotechnology indices in 1992 for these same subfields (Miller, 1992). PaineWebber graciously made available the list of firms they used to create the indices in each subfield.

[16] The formulation for this measure of uncertainty had implications for how the indices where constructed. To assure that the measures of uncertainty were comparable across subfields and across time, each index contained nine firms throughout its life. The size of the indices (number of firms) was constrained because biotechnology was a very young industry in 1984, with relatively few public companies. Since public companies were particularly rare in the Ag/Bio subfield, we

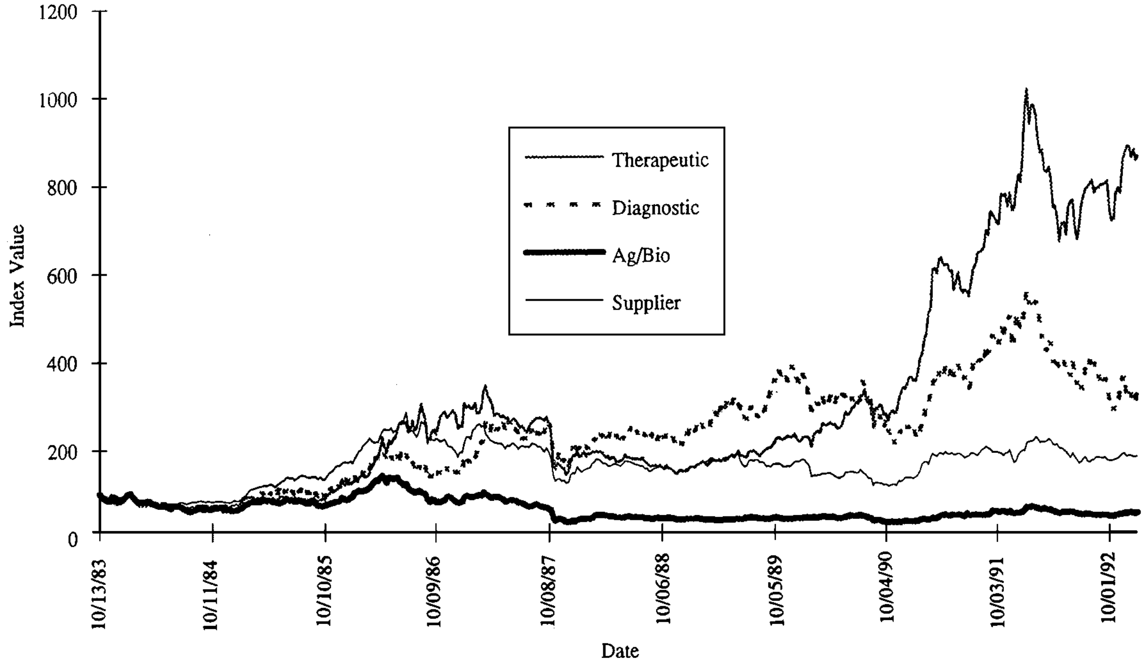

Figure 2. Inflation-adjusted index values for biotechnology segments (1984–92)

$$\sigma_w^2 = \left(\frac{1}{26-1}\right) \times \sum_{t=1}^{26} \left[(\log R_t)^2 - \mu^2 \right] \quad (2)$$

where

σ_w = the unbiased estimate of the 26-week volatility;

R_t = (I_t/I_{t-1}), represents the inflation-adjusted index price relative for week t;

$$\mu = \left(\frac{1}{26}\right) \times \sum_{t=1}^{26} \log R_t.$$

The 26-week measure was chosen because it was believed that volatility one-half year prior to the transaction accounts for most of the influence on the governance choice decision.[17] Technological uncertainty was converted to a monthly measure because the announcement dates for the transactions are monthly.[18]

Number of rivals

The value of deferring acquisition is expected to decrease with an increasing number of R&D rivals. To represent the number of rival firms, we use the number of biotechnology firms with R&D programs in subfield m at time t. This measure should be appropriate because biotechnology firms are the primary source of technology in the industry (Office of Technology Assessment, 1984). Annual data on the number of biotechnology firms in each subfield were available from the Office of Technology Assessment (1984), and the Ernst & Young surveys (Burrill, 1987–93).

Control variables

There are factors, unrelated to the cost of commitment, which should have a bearing on governance

were limited by the number of public firms in that subfield, and thus, in all subfields.

[17]A 52-week measure of technological volatility was also considered and tested. The coefficients for the 52-week measure were generally less significant, supporting our choice of the 26-week measure.

[18]The monthly measure of volatility is: $\sigma_m = \left(\frac{1}{k}\right) \times \sum_{w=1}^{k} (52\sigma_w)$, where k equals the number of weeks in a month.

choice. As discussed earlier, transaction cost theory has played an important role in previous work.

R&D expense

R&D expense has been widely used to proxy the degree of proprietary content and to represent the level of human and dedicated capital specific to a transaction (Levy, 1985; Caves and Bradburd, 1988; Gatignon and Anderson, 1988; Hennart, 1991). As reported earlier, given higher levels of asset specificity greater degrees of integration will be favored. No direct information on firm-level R&D spending was available for the private firms in our sample, so the measure of asset specificity we employ is the R&D intensity (the ratio of R&D expense to total expense) ratio of the technical subfield to which the target firm belongs.[19] The measure was calculated for five different years from data reported in the Ernst & Young annual surveys (Burrill, 1989–93). Like Arora and Gambardella (1994), we found little variance in the ratio over time, so the 5-year average of the ratio was used. The ratio of R&D expense to total expenses for the various subfields is 49.0 percent for Therapeutics, 28.0 percent for Diagnostics, 42.0 percent for Ag/Bio, and 11.5 percent for Supplier. Because Williamson (1991) advocated a curvilinear relationship between asset specificity and governance choice, we transformed R&D Expense by taking its exponential.

U.S. transaction

Transactions in an international context usher in two problems which play minor roles in domestic trading. Culture and political differences between firms from different countries may complicate the integration process, reinforcing the transaction cost arguments for market mediation and weakening incentives to acquire firms in other countries (Kogut and Singh, 1988; Hennart, 1991). Transactions between two firms in the same country should not be exposed to such problems. Project *j* was classified as a U.S. Transaction and coded '1' if it involved two firms from the United States. Where the biotechnology firm was the only firm domiciled in the United States, this measure was coded '0'.

Interest rates

While real options are affected by interest rates, the net effect is weak and sometimes even ambiguous (Dixit and Pindyck, 1994). The higher the interest rate, the lower the present value of the exercise price as contracted upon in the collaboration. As a result, a higher interest rate will have the same effect as lowering the exercise price. However, this influence is moderated by the fact that higher interest rates also lower the present value of owning the technology outright. As a result, we do not expect a significant relationship for interest rates, but include it to control for its possible effects. The relevant measure is the risk-free interest rate corresponding to the duration of project *j* at initiation of project *j*. The average monthly yield of United States Treasury Securities was used, as reported in the Federal Reserve Bulletin (U.S. Board of Governors of the Federal Reserve System (1984–93).

Sub-field level effects

To control for biotechnology subfield level effects other than those reflected in Technology Value, Technological Uncertainty, Number of Rivals, R&D Expense, dummies were included to identify transactions in the therapeutic and supplier/specialty chemical subfields. Further distinctions among Diagnostics and Ag/Bio subfields were not possible because they would be perfectly collinear with the Number of Rivals and R&D Expense variables. The two subfields chosen appear to demonstrate the most independence with regard to governance selection.

Descriptive statistics

Table 1 presents descriptive statistics for the dependent and independent variables in the entire sample and in each subfield. The means for the dependent variable represent frequencies for each

[19] Gatignon and Anderson (1988) have used a similar industry-level measure of R&D expense as a proxy for the degree of asset specificity in a particular transaction. In contrast to theirs and other studies having gauged asset specificity using R&D expenditures as a percentage of sales (Levy, 1985; Caves and Bradburd, 1988; Hennart, 1991; Arora and Gambardella, 1994), our study places total expenses in the denominator because the majority of biotechnology firms lack sales income. Total expenses include cost of product sales, general and administrative expenses, marketing and selling expenses, R&D expenses, interest expense, and miscellaneous expenses.

Table 1. Variable definitions and descriptive statistics (402 transactions)

Variable	Total sample $n = 402$ Means	Total sample $n = 402$ S.D.	Therapeutic subfield $n = 199$ Means	Diagnostic subfield $n = 76$ Means	Ag/Bio subfield $n = 70$ Means	Supplier subfield $n = 57$ Means
Choice variables						
1. Acquisition and Merger	0.52		0.38	0.66	0.60	0.73
2. Minority Investment	0.38		0.51	0.28	0.24	0.23
3. Joint Venture	0.10		0.11	0.07	0.16	0.04
Independent variables						
1. U.S. Transactions	0.61	0.49	0.58	0.67	0.60	0.67
2. Interest Rates	7.86	1.35	8.17	7.41	8.15	7.02
3. R&D Expense	38.57	13.31	49.00	28.00	42.00	12.00
4. Dissimilar Partners	0.60	0.49	0.65	0.45	0.59	0.63
5. (log) Technology Value	5.28	0.90	5.75	5.51	3.82	5.13
6. Technological Uncertainty	0.33	0.12	0.33	0.33	0.36	0.26
7. (log) Number of Rivals	5.28	0.52	5.55	5.36	4.63	5.05

governance mode. 61.0 percent of all transactions involve two U.S. firms. Number of Rivals and Technological Value were transformed by taking their natural logarithm to correct for the positive skewness in these variables. Table 2 presents the correlations among the independent variables.

Methodology

To estimate the impact of the independent variables, X_i, on the probability that minority investment, joint venture, or acquisition would be selected for the ith transaction, both a binary and a multinomial logit model were used. Multinomial logit is used to assess whether the determinants of the utility are different for each of these possible modes. However, since we have not theoretically specified how preferences for joint ventures and minority investments should systematically differ, a binary logit is used initially to collapse equity collaborations (minority investments and joint ventures) into one choice mode. Because binary logit is a simplification of the multinomial model, we describe the multinomial model in detail.

Let G_i be the governance mode of the ith transaction selected by the acquiring firm. The multinomial logit model can be expressed as

Table 2. Pearson correlation coefficients ($n = 402$)

Independent variables	1	2	3	4	5	6	7	8
1. Therapeutics subfield								
2. Supplier/Specialty Chemical subfield	–0.40							
3. U.S. Transactions	–0.06	0.04						
4. Interest Rates	0.23	–0.25	–0.08					
5. R&D Expense	0.78	–0.81	–0.07	0.32				
6. Dissimilar Partners	0.10	0.03	–0.28	0.22	0.07			
7. (log) Technology Value	0.52	–0.07	–0.00	0.00	0.14	–0.13		
8. Technological Uncertainty	0.04	–0.25	0.05	–0.21	0.16	–0.02	–0.02	
9. (log) Number of Rivals	0.51	–0.18	–0.07	–0.34	0.25	–0.15	0.86	0.02

Correlations greater than ± 0.098 are significant at $p < 0.05$

$$P_{ij} = P(G_i = j/X_i) = \left(\frac{e^{X_i \beta_j}}{\sum_{j=1}^{3} e^{X_i \beta_j}} \right) \qquad (3)$$

where

P_{ij} is the probability that transaction i is of the governance mode j where $j \in (1,2,3)$. The feasible choice set includes minority investments, joint ventures, and acquisitions;[20]

β_j is the vector of coefficients of the marginal utilities of each of the independent variables.

RESULTS

Model significance

We tested the significance of the theoretical model (Table 3) by examining whether the addition of the independent variables significantly improved the ability to explain the choice between equity collaboration (either joint venture or minority investment) and acquisition. A log-likelihood ratio test was used to compare the full model (column 3) to a nested naïve model (column 1) including the subfield dummies, the country dummy, interest rates, and R&D Expense. The naïve model reflects the degree of asset specificity and the potential for cultural difficulties, two important variables used in traditional transaction cost specifications for the choice of governance. The log-likelihood ratio test produced a chi-square value of 54.0 with 5 degrees of freedom, which indicates that the incremental fit in the model from including the option variables is significant by any standards ($p < 0.0001$).

Hypothesis testing

Columns (1–3) present three binary models testing the effects of the independent variables on the likelihood of choosing equity collaboration over acquisition. Column (2) adds the explanatory variables specified in the theoretical discussion. Column (3) includes the interaction variable between Technological Uncertainty and R&D Expense. Each of these models demonstrates strong support for the hypotheses.

The theoretical discussion hypothesizes that greater dissimilarity between partners will lead to an increased preference for equity collaborations. Consistent with these expectations, t-tests revealed that the coefficient Dissimilar Partners has a positive and highly significant ($p < 0.001$) relationship with the likelihood of choosing equity collaboration. Thus, Hypothesis 1 receives strong support.

In Hypotheses 2–4 we argue that equity collaborations will be preferred to acquisition in technical subfields with more growth opportunities, greater technological uncertainty, and fewer rivals. t-Tests revealed support for each of these hypotheses at a high level of confidence ($p < 0.01$). These findings provide strong support for Hypotheses 2, 3, and 4.

Hypothesis 5 suggests that the effect of technological uncertainty should be greatest in domains of high asset specificity. We examined this expectation through an interaction term introduced in column (3). Using a log-likelihood ratio test, we found that the interaction term between technological uncertainty and R&D Expense significantly contributed to model fit ($p < 0.05$). This test produced a chi-square value of 4.82 at 1 degree of freedom. A t-test revealed that the interaction term was significant ($p < 0.05$) and positive, as expected. The marginal importance of technological uncertainty in the governance choice decision is greater in domains of high asset specificity.

Control variables

The results in Table 3 also illustrate important findings regarding control variables. Column (3) reveals that the variable R&D Expense has a negative and significant effect on the likelihood of initiating equity collaborations. This result lends support to transaction cost theory, since greater asset specificity is expected to lead to an

[20] One may argue that there exist additional external governance modes for acquiring know-how, such as licensing agreements or research agreements (without equity), and that these modes may substitute for either equity agreements or acquisition. Whether this exclusion biases the multinomial logit results is an empirical question. In a study on governance choice in the biotechnology industry, Folta and Leiblein (1994) confirmed that excluding nonequity forms of collaboration does not bias the explanatory variables. They analyzed the choice between nonequity collaboration, equity collaboration, and acquisition. In testing the assumption of Independence of Irrelevant Alternatives, they indirectly confirmed that excluding nonequity collaborations did not alter the coefficients for the other two alternatives.

Table 3. Binary logit parameter estimates for choice of governance: Equity collaboration preferred to acquisition

Independent variables	(1)	(2)	(3)
Constant	–2.6864***	–1.8064	–2.4372
	(0.774)[a]	(2.567)	(2.601)
Therapeutic subfield	0.9302**	0.6352	0.4463
	(0.291)	(0.587)	(0.598)
Supplier/Specialty Chemical subfield	–0.3515	–0.7580	–0.8695
	(0.404)	(0.533)	(0.541)
U.S. Transactions	–0.6003**	–0.4900*	–0.5436*
	(0.219)	(0.245)	(0.248)
Interest Rate	0.2370**	0.2590*	0.3142*
	(0.875)	(0.130)	(0.134)
R&D Expense[b]	–0.0035	–0.2289	–0.2211*
	(0.025)	(0.370)	(0.106)
Dissimilar Partners		1.2290***	1.2685***
		(0.252)	(0.2567)
log (Technology Value)		0.9262**	1.0042**
		(0.334)	(0.340)
Technological Uncertainty		3.3569**	2.2193**
		(1.068)	(1.095)
Number of Rivals		–1.4386**	–1.4209**
		(0.480)	(0.480)
Technological Uncertainty × R&D Expense[b]			0.5823*
			(0.292)
Log-likelihood statistic, £(β)	–386.35	–361.76	–359.35

†$p < 0.10$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

402 transactions

Null Model: £(0) = –441.64; 0 d.f.
[a]Standard errors in parentheses.
[b]Coefficients and standard errors should be multiplied by ($\times 10^{-11}$).

increased preference for acquisition over less-integrative modes. Also consistent with transaction cost theory is the finding that transactions involving two firms domiciled in the United States were more likely to choose acquisition over equity collaborations. This result was expected because domestic transactions are not susceptible to the high costs of integrating business across borders. Both these results fill a needed void in empirical work which has given little attention to the choice between equity collaboration and acquisition.

Consistent with option arguments, there is a positive and significant relationship between Interest Rates and the likelihood of selecting equity collaboration. While the coefficient for the therapeutic subfield was significant in column (1), neither coefficients for the subfield dummies were significant (Models (2) and (3)).

Differences between minority investments and joint ventures

The preceding analysis examines the effects of independent variables on the likelihood of choosing equity collaboration alternatives to acquisition. It does not, however, distinguish between the two types of equity collaboration: minority investment and joint venture. While both provide options on growth opportunities, there may be differences between minority investments and joint ventures in the value of the option they provide. This is because minority investments may provide exposure to the target firm's full portfolio of technological capabilities, while joint ventures expose only those capabilities brought to the venture. Since joint ventures only encompass a portion of the target's technological capability, the growth option is somewhat diminished relative to minority investment or acquisition. As a result, there is likely to be an opportunity cost associated with owning an option on a venture rather than the firm itself. A significant opportunity cost may mitigate the incentive to defer acquisition. As a result, the value of the option to defer acquisition may differ between minority investments and joint ventures.

To examine whether the explanatory variables have similar effects on the preference for minority investments and joint ventures, we ran a trinomial model (not shown), with the choices being minority investment, joint venture, and acquisition. The fundamental assumption underlying discrete choice modeling is the independence of irrelevant alternatives (IIA). The IIA assumption requires that for any two alternatives the ratio of their choice probabilities is independent of the systematic utilities of any other alternatives in the choice set. The most widely accepted test of the validity of the IIA assumption has been developed by Hausman and McFadden (1984). Initiation of this test on our trinomial specification reveals a Hausman statistic of 14.736. This statistic falls below the critical value ($X^2_{8\mathrm{df}}$) of 15.51 at a 95 percent confidence level. Hence, we cannot reject the null hypothesis that all three alternatives are independent of one another. This result is interesting considering that previous studies, including our earlier analysis, have combined minority investments and joint ventures into one alternative (Pisano, 1989a, 1989b; Hennart, 1991).

Table 4. Multinomial logit parameter estimates for choice of governance: Acquisition, minority investment, and joint venture

Independent variables	Min. investment preferred to acquisition	Joint venture preferred to acquisition
Constant	−2.3065	
	(2.599)	
Therapeutics subfield	0.4909	
	(0.599)	
Supplier/Specialty Chemical subfield	−0.8385	
	(0.542)	
U.S. Transactions	−0.5475*	
	(0.248)	
Interest Rate	0.3170*	
	(0.134)	
R&D Expense[b]	−0.2260*	
	(0.106)	
Dissimilar Partners	1.5218***	0.4599
	(0.281)[a]	(0.382)
log (Technology Value)	1.1911**	0.4554
	(0.353)	(0.432)
Technological uncertainty	2.2864*	3.9292**
	(1.160)	(1.411)
Number of Rivals	−1.5626**	−1.0486*
	(0.490)	(0.563)
Technological uncertainty × R&D expense[b]	0.6197*	0.5685†
	(0.297)	(0.300)
Log-likelihood statistic, £(β)	−315.53	

†$p < 0.10$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

402 transactions

[a]Standard errors in parentheses.

[b]Coefficients and standard errors should be multiplied by ($\times 10^{-11}$).

To examine whether significant differences existed across the vector of option coefficients, a log-likelihood ratio test was used. The full model in Table 4 was compared to the restricted model in Table 3 (column 3). The full model includes two vectors of option coefficients: one specific to the preference for minority investments over acquisition, and the other specific to the preference for joint ventures over acquisition. Like the binary models in Table 3, the remaining coefficients in the full model are specific to both minority investments and joint ventures. This test revealed a test statistic of 87.64 with 5 degrees of freedom—a value which greatly exceeds the critical $X^2_{(0.01)}$ value of 15.09. Thus, we can conclude that the addition of the vector of option coefficients specific to minority investments is different than the vector specific to joint ventures.[21]

It is useful to know if the rejection of the null hypothesis (that the vector of option coefficients is the same for minority investments and joint ventures) can be attributed to individual coefficients. This was done by comparing coefficients for each variable with respect to the alternatives

[21]The effects of other control variables were also tested, but not reported in tables. The theoretical model specified earlier suggested that the preference for joint ventures relative to acquisitions should be influenced by *the capabilities which the target firm brings to the venture*. The *NCBC Companies Database* and *BioScan* were used to create a variable representing this construct. A model incorporating this variable revealed that the parameter estimates of the remaining variables were affected little.

of minority investment and joint venture.[22] The appropriate statistic for this test is a *t*-statistic. This analysis revealed that significant differences existed for Dissimilar Partners ($t = 2.73$), Technology Value ($t = 2.07$), and Number of Rivals ($t = 1.31$). More specifically, we found that minority investments would be preferred over joint ventures when there are dissimilar partners (two-tailed test, $p < 0.01$) and when technology value is high (two-tailed test, $p < 0.05$). Conversely, joint ventures are preferred to minority investments when there are a greater number of rivals (one-tailed test, $p < 0.10$).

DISCUSSION

This study has challenged the view that higher domains of asset specificity require more integrative modes of governance. We argue that under certain conditions there may be significant costs to committing immediately to acquisition, and that these costs may offset the benefits associated with superior administrative control. In particular, we have discussed the relative importance of endogenous uncertainty in motivating sequential investment and the value of deferring commitment during periods of technological uncertainty. These types of uncertainty should have increased relevance to governance when investment activity is largely dominated by the potential for growth opportunities. Since firms can initiate minority investments or joint ventures to ensure an opportunity to acquire a target firm or venture, they are well positioned to benefit from the increases in the value of the technology, while limiting downside exposure. Option theory provides a framework for evaluating the costs of committing to a technology with an uncertain value. This paper is the first, we believe, to document empirical support for the assertion that the choice between equity collaborations and acquisition is influenced by the cost of commitment. Since real option theory has not previously been systematically applied to the governance decision, our findings are promising and suggest that the option framework is a valuable tool for understanding governance choice. Several of these findings are worth highlighting.

Discussion of results

First, we found that dissimilar partners are more likely to prefer equity collaboration than acquisitions. Previous studies have argued that information asymmetry between partners will lead to a failure in the market for acquisition (Balakrishnan and Koza, 1993), but have not tested whether it leads to a preference for equity collaborations. Our result supports the view that information asymmetry plays an important role in governance choice, but more broadly, suggest that endogenous uncertainty is best resolved through sequential investment or transitional governance. In this sense, we provide support for the work of Kogut and Zander (1992); and we also support Williamson's (1988) claim that transitional governance may be appropriate in domains where learning is critical.

Second, we found that technical subfields with higher growth opportunities are more attractive for exploratory investment, tending to increase the likelihood of choosing equity collaborations. Where growth opportunities are a larger component of investment activity, firms increasingly prefer sequential governance to outright acquisition.

Third, our findings suggest that technological uncertainty increases the likelihood of choosing equity collaboration. We have argued that technological uncertainty raises the incentive to defer internalization of R&D activities. This result is particularly promising because we focused significant attention on constructing an uncertainty measure to mirror that implied in the Black and Scholes (1973) model. Previous efforts to operationalize this construct do not capture its rich nature. Many studies focus on specific industries that represent 'uncertain' markets. Others use time measures which do not purely capture uncertainty, and have the problem of concealing important differences across segments in an industry. Using a measure based on stock market data, we were able to discern the effects of technological uncertainty, even after controlling for technological uncertainty by sampling on an industry that is highly volatile. It is worth noting that the significance for this measure was robust, even to a

[22] The test statistic for the null hypothesis $\beta_{MI} = \beta_{JV}$ is given by

$$\frac{\hat{\beta}_{MI} - \hat{\beta}_{JV}}{\sqrt{\mathrm{var}(\hat{\beta}_{MI} - \hat{\beta}_{JV})}}, \text{ where } \mathrm{var}(\hat{\beta}_{MI} - \hat{\beta}_{JV}) = \mathrm{var}(\hat{\beta}_{MI}) + \mathrm{var}(\hat{\beta}_{JV}) - 2\,\mathrm{cov}(\hat{\beta}_{MI}, \hat{\beta}_{JV})$$

stock market crash.[23] Since indices are used on Wall Street for virtually every industry (and subfields within the industry), this form of measurement offers great potential for future research.

We also found a greater preference for equity collaborations in technical subfields that are more rivalrous. This result supports the view that an increased likelihood of preemption decreases the incentive to defer commitment (Trigeorgis, 1991; Kulatilaka and Perotti, 1995).

Finally, we examined whether differences exist in the option relationships tied to minority investments and joint ventures. In general, the coefficients appear very similar for both minority investments and joint ventures. However, testing revealed that the vectors of option coefficients were different between minority investments and joint ventures. This difference between vectors is due predominantly to the effect of partner similarity. Evidently, dissimilar partners do seem to prefer minority investment over acquisition, but do not prefer joint venture over acquisition. This result is somewhat inconsistent with previous arguments and should receive attention in future studies. However, it may be due to the limited number of joint ventures in the sample. These tests suggest that combining minority investments and joint ventures into one alternative, as has been done in the past, may potentially hide important differences. Future research should further examine differences between minority investments and joint ventures.

Implications for transaction cost theory

It is important to note that our work in no way discredits transaction cost theory. On the contrary, our results lend support to this perspective. Absent information asymmetry and endogenous uncertainty, the market for acquisition does not fail. We also found that transactions in subfields with higher levels of R&D expenses were more likely to involve acquisitions than equity collaborations. This suggests that acquisitions provide administrative controls superior to equity collaborations for dealing with problems created by opportunistic partners. This finding lends added credibility to the power of transaction cost theory in explaining different degrees of ownership.

By focusing on an environment (biotechnology) where developing capabilities and exploring growth opportunities are central to investment activity, we examine a domain where equilibrium contracting may not fully apply. Our analysis provides insight into the conditions where exploration occurs most efficiently and highlights the conditions where the risk of commitment offsets the benefits of administrative control. In particular, we found that technological uncertainty plays an increasingly important role in the preference for equity collaboration in domains of higher asset specificity. This finding has several important implications. It highlights the importance of transitional governance when transaction cost theory predicts that integration provides superior administrative control. It also suggests that transitional governance is less important when asset specificity is lower. Hence, our results and theoretical development help to identify conditions where transaction cost theory can be advised by other perspectives. These conditions include when: (a) exploration is key to investment activity; (b) asset specificity is high; (c) learning occurs in distantly related areas; and (d) technological uncertainty is high.

Several of the variables we used to examine the cost of commitment may also be argued to represent a need for more administrative control. A central tenet of Williamson is that greater uncertainty is expected to be associated with a need for greater administrative control. While our results indicate that equity collaborations are preferred under higher uncertainty, they do not necessarily dispute Williamson's claim. Rather, the point is that technological uncertainty also escalates the cost of immediate commitment, particularly in domains where learning and exploration are the dominant motive.

Our measure of number of rivals has been used in previous studies (Pisano, 1989a, 1989b) as a proxy for the likelihood of 'small numbers bargaining' conditions. It has been argued that more potential partners should increase the competitive environment and decrease the incentive for partners to behave opportunistically, leading to an decreased likelihood of acquisition. How-

[23] We also ran two other models: (a) a model excluding data in the time period during and shortly after the 1987 stock market crash (9/87–6/88); and (b) a model including a variable which corresponds to the NASDAQ monthly average over the life of the sample. Our results for both models demonstrated extremely similar coefficients as was demonstrated in Table 3, column (3).

ever, there is some theoretical evidence which suggests that this proxy for small numbers conditions does not hold in R&D-intensive industries (Williamson, 1985: 61).[24] Since our finding is opposite of this transaction cost expectation, we conclude that this variable more robustly captures a devaluation in the option to defer internalization.

Finally, we have maintained that the option to defer acquisition may create cash flow advantages relative to outright acquisition, and recognize that transaction costs play an important role in the initial structuring of the rights. Restrictions on either partner's rights to buy out the other can be used to prevent premature termination of a relationship. The specific provisions for buy-outs can be structured to reduce the gains from termination.

Implications for governance choice

While we recognize that equity collaborations provide an option to defer internal development, we also suggest that they are attractive, in part, because they provide an option to defer acquisition. The rights accompanying these transactions serve to facilitate upside gains and preempt competitors. This highlights the necessity to negotiate effectively at the outset of the agreement, in order to secure rights on future equity or on the technology itself. To the extent that the investing firm can involve itself in the active development of the technology and the operations of the target firm, perhaps through board representation, it will increase its understanding of the true value of the technology relative to potential competitors.

The presence of commercialization rights in the terms of the equity agreement suggests a willingness on the part of the seller to provide such rights. We do not explicitly examine why technology sellers may be willing to forgo future earnings and subject themselves to future buyout by the partner. It likely stems from asymmetric bargaining power during the negotiation process of the equity agreement. Of course, the ability to favorably negotiate such conditions depends largely on the leverage the partners bring to the bargaining table. An investing firm with more complementary assets, such as marketing expertise, research laboratories, a national or global distribution network, or experience in dealing with regulatory agencies, will prove a more valuable partner to the target firm and is more likely to garnish a favorable position. At the same time, a target firm which lacks the necessary resources for further development and commercialization may be more willing to grant such rights to the investor. The investing firm should carefully evaluate and act upon its leverage to ascertain rights which enhance its option value. Future research should examine the impact of firm resources and capabilities on the value of deferring acquisition.

Firm resources and capabilities may have implications beyond the negotiation stage in the equity collaboration. Firms which have high learning capabilities (Kogut and Zander, 1992; Cohen and Levinthal, 1990), are embedded in a network, or have administrative experience with collaborations (Powell, Koput, and Smith-Doerr, 1996) can learn quicker and more efficiently through collaborative modes compared to firms without such capabilities. As a result, the marginal disadvantage of technology transfer across organizational boundaries may be reduced for firms with absorptive capacity or collaborative experience.[25] These firms should show an increased preference for equity collaboration to acquisition. While previous studies have examined the influence of these variables on the incidence of collaboration, no study that we know of has examined how these variables influence the choice between acquisition and collaboration.

In summary, this research draws attention to the theoretical and empirical implications of committing in environments characterized by high uncertainty and where investment activity is dominated by growth opportunities. In such environments, it offers a theoretical explanation for the preference for minority investments and joint ventures over acquisition. Furthermore, it is

[24]Williamson (1985) has suggested that when transactions involve investments in transaction-specific human or physical assets, a bilateral contracting condition will result after the initial governance decision has been made, even in the presence of many potential partners. This conveys an advantage on the winning technology supplier, but it aggravates the potential for opportunism for the technology buyer, which should be recognized *a priori*.

[25]A similar argument, although one distinguished from the learning one we present, is that experience with a specific partner or embeddedness in a network may reduce the risk of opportunism, and hence the need to internalize activities.

the first study, we believe, to find empirical support for the dual role that the option to defer and the option to grow play in the initiation of equity collaborations. Future work should examine whether other modes of governance can offer similar benefits. Although a limited number of questions were addressed in this study, it is hoped that the theoretical discussion and research findings reported here have improved the current understanding and awareness of the importance of option thinking, and that it can make a contribution in the context of governance choice.

ACKNOWLEDGEMENTS

I would like to thank Arnold Cooper, Bruce Kogut, Kent Miller, and seminar participants at Wharton for their valuable comments on an earlier draft. I am especially grateful to Dan Schendel, not only as editor of this journal, but as a guiding force throughout this research. All errors remain my own. Financial support for this study was provided by the Purdue Research Foundation, the Technology Transfer Initiative at Purdue University, and the Center for International Business Education and Research.

REFERENCES

Akerlof, G. A. (1970). 'The market for lemons: Qualitative uncertainty the market mechanism', *Quarterly Journal of Economics*, **84**, pp. 488–500.

Armour, H. O. and D. J. Teece (1980). 'Vertical integration and technological innovation', *Review of Economics and Statistics*, August, pp. 470–474.

Arora, A. and A. Gambardella (1994). 'Evaluating technological information and utilizing it', *Journal of Economic Behavior and Organization*, **24**, pp. 91–114.

Arrow, K. (1962). 'Economic welfare and the allocation of resources for invention'. In R. Nelson (ed.), *The Rate and Direction of Inventive Activity*. Princeton University Press, Princeton, NJ, pp. 609–625.

Balakrishnan, S. and M. P. Koza (1993). 'Information asymmetry, adverse selection and joint-ventures', *Journal of Economic Behavior and Organization*, **20**, pp. 99–117.

Balakrishnan, S. and B. Wernerfelt (1986). 'Technical change, competition and vertical integration', *Strategic Management Journal*, **7**(4), pp. 347–359.

Black, F. and M. Scholes (1973). 'The pricing of options and corporate liabilities', *Journal of Political Economy*, **81**, pp. 637–659.

Bulow, J., M. Huang and P. Klemperer (1996). 'Toeholds and takeovers', Stanford University working paper.

Burrill, G. S. (1987–93). *Biotechnology Industry Reports*. Ernst & Young High Technology Group, San Francisco, CA.

Cainarca, G. C., M. G. Colombo and S. Mariotti (1992). 'Agreements between firms and the technological life cycle model: Evidence from informational technologies', *Research Policy*, **21**, pp. 45–62.

Caves, R. E. and R. M. Bradburd (1988). 'The empirical determinants of vertical integration', *Journal of Economic Behavior and Organization*, **9**, pp. 265–279.

Chi, T. (1994). 'Trading in strategic resources: Necessary conditions, transaction costs problems, and choice of exchange structure', *Strategic Management Journal*, **15**(4), pp. 271–290.

Cohen, W. M. and D. A. Levinthal (1990). 'Absorptive capacity: A new perspective on learning and innovation', *Administrative Science Quarterly*, **35**(1), pp. 128–152.

Cukierman, A. (1980). 'The effects of uncertainty in investment under risk neutrality with endogenous information', *Journal of Political Economy*, **88**, pp. 462–475.

Dibner, M. D. (1992). 'U.S. biotechnology and pharmaceuticals', *BioPharm*, **5**(8), pp. 24–28.

Dierickx, I. and K. Cool (1989). 'Asset stock accumulation and sustainability of competitive advantage', *Management Science*, **35**(12), pp. 1504–1511.

Dixit, A. K. and R. S. Pindyck (1994). *Investment Under Uncertainty*. Princeton University Press, Princeton, NJ.

Folta, T. B. (1994). 'Innovation through quasi-integration: An application of option theory to governance decisions in the biotechnology industry', unpublished doctoral dissertation, Purdue University.

Folta, T. B. and M. J. Leiblein (1994). 'Technology acquisition and the choice of governance by established firms: Insights from option theory in a multinomial logit model', *Academy of Management Proceedings*, Dallas, TX.

Friar, J. and M. Horwitch (1985). 'The emergence of technological strategy: A new dimension of strategic management', *Technology in Society*, **7**, pp. 50–85.

Garvey, G. (1993). 'Does hierarchical governance facilitate adaptation to changed circumstances? Some formal examples', *Journal of Economic Behavior and Organization*, **20**, pp. 187–211.

Gatignon, H. and E. Anderson (1988). 'The multinational corporation's degree of control over foreign subsidiaries: An empirical test of a transaction cost explanation', *Journal of Law, Economics, and Organization*, **4**(2), pp. 305–336.

Gomes-Casseres, B. (1989). 'Ownership structures of foreign subsidiaries', *Journal of Economic Behavior and Organization*, **11**, pp. 1–25.

Grossman, S. and O. Hart (1986). 'The costs and benefits of ownership: A theory of vertical and lateral integration', *Journal of Political Economy*, **94**, pp. 691–719.

Hagedoorn, J. and J. Schakenraad (1990). 'Strategic partnering and technological cooperation'. In B. Dankbaar, J. Groenewegen and H. Schenk (eds.), *Perspectives in Industrial Economics*. Kluwer, Dordrecht, pp. 171–194.

Harrigan, K. R. (1985). 'Vertical integration and corporate strategy', *Academy of Management Journal*, **28**(2), pp. 397–425.

Hausman, J. A. and D. L. McFadden (1984). 'Specification tests for the multinomial logit model', *Econometrica*, **52**(5), pp. 1219–1240.

Hennart, J.-F. (1991). 'The transaction costs theory of joint ventures: An empirical study of Japanese subsidiaries in the United States', *Management Science*, **37**(4), pp. 483–497.

Hurry, D., A. T. Miller and E. H. Bowman (1992). 'Calls on high-technology: Japanese exploration of venture capital investments in the United States', *Strategic Management Journal*, **13**(2), pp. 85–102.

Jensen, M. C. (1993). 'The modern industrial revolution, exit, and the failure of internal control systems', *Journal of Finance*, **48**(3), pp. 831–880.

Kester, W. C. (1984). 'Today's options for tomorrow's growth', *Harvard Business Review*, **62**(2), pp. 153–160.

Kogut, B. (1988). 'Joint ventures: Theoretical and empirical perspectives', *Strategic Management Journal*, **9**(4), pp. 319–332.

Kogut, B. (1991). 'Joint ventures and the option to expand and acquire', *Management Science*, **37**(1), pp. 19–33.

Kogut, B. and N. Kulatilaka (1994). 'Options thinking and platform investments: Investing in opportunity', *California Management Review*, Winter, pp. 52–71.

Kogut, B. and H. Singh (1988). 'The effects of national culture on the choice of entry mode', *Journal of International Business Studies*, **49**, pp. 411–430.

Kogut, B. and U. Zander (1992). 'Knowledge of the firm, combinative capabilities, and the replication of technology', *Organizational Science*, **3**(3), pp. 383–397.

Kogut, B. and U. Zander (1993). 'Knowledge of the firm and the evolutionary theory of the multinational corporation', *Journal of International Business Studies*, 4th Quarter, pp. 625–645.

Kulatilaka, N. and E. C. Perotti (1995). 'What is lost by waiting to invest?', Boston University working paper.

Levy, D. T. (1985). 'The transactions cost approach to vertical integration: An empirical examination', *Review of Economics and Statistics*, **67**, pp. 438–455.

Madhok, A. (1997). 'Cost, value, and foreign market entry mode: The transaction and the firm', *Strategic Management Journal*, **18**(1), pp. 39–61.

Majd, S. and R. Pindyck (1987). 'Time to build, option value, and investment decisions', *Journal of Financial Economics*, **18**, pp. 7–27.

Mansfield, E., J. Rapoport, J. Schnee, S. Wagner and M. Hamburger (1971). *Research and Innovation in the Modern Corporation*. W. W. Norton, New York.

March, J. G. (1991). 'Exploration and exploitation in organizational learning', *Organizational Science*, **2**, pp. 71–87.

McDonald, R. and D. Siegel (1986). 'The value of waiting to invest', *Quarterly Journal of Economics*, **101**, pp. 707–728.

Miller, L. (1992). *Biotechnology Industry 1992 Fact Book*. Painewebber, New York.

Miller, M. H. and F. Modigliani (1961). 'Dividend policy, growth and the valuation of shares', *Journal of Business*, **34**, pp. 411–463.

Mitchell, W. G. (1988). 'Dynamic commercialization: An organizational economic analysis of innovation in the medical diagnostic imaging industry', unpublished doctoral dissertation, University of California at Berkeley.

Mitchell, W. and K. Singh (1992). 'Incumbents' use of pre-entry alliances before expansion into new technical sub-fields of an industry', *Journal of Economic Behavior and Organization*, **18**, pp. 347–372.

Mody, A. (1993). 'Learning through alliances', *Journal of Economic Behavior and Organization*, **20**, pp. 151–170.

Myers, S. C. (1977). 'Determinants of corporate borrowing', *Journal of Financial Economics*, **5**, pp. 147–175.

Nanda, A. and P. J. Williamson (1995). 'Use of joint ventures to ease the pain of restructuring', *Harvard Business Review*, **73**(6), pp. 119–128.

Nelson, R. and S. Winter (1977). 'In search of useful theory of innovation', *Research Policy*, Summer, pp. 36–76.

North Carolina Biotechnology Center Actions Database (1993). North Carolina Biotechnology Center, Research Triangle Park, NC.

Office of Technology Assessment (1984). *Commercial Biotechnology: An International Analysis, OTA-BA-218*. U.S. Congress, Washington, DC.

Oryx Press (1992 and earlier editions). *BioScan: The Worldwide Biotech Industry Reporting Service*. Oryx Press, Phoenix, AZ.

Pindyck, R. S. (1991). 'Irreversibility, uncertainty, and investment', *Journal of Economic Literature*, **29**, pp. 1110–1152.

Pisano, G. (1988). 'Innovation through markets, hierarchies, and joint ventures: Technology strategy and collaborative arrangements in the biotechnology industry', unpublished doctoral dissertation, University of California at Berkeley.

Pisano, G. (1989a). 'The R&D boundaries of the firm: An empirical analysis', *Administrative Science Quarterly*, **35**(1), pp. 153–176.

Pisano, G. P. (1989b). 'Using equity participation to support exchange: Evidence from the biotechnology industry', *Journal of Law, Economics, and Organization*, **5**(1), pp. 109–126.

Porter, M. E. (1980). *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. Free Press, New York.

Porter, M. E. and M. B. Fuller (1987). 'Coalitions and global strategy'. In M. E. Porter (ed.), *Competition in Global Industries*. Harvard Business School Press, Boston, MA, pp. 315–344.

Powell, W. W., K. W. Koput and L. Smith-Doerr (1996). 'Interorganizational collaboration and the locus of innovation: Networks of learning in biotechnology', *Administrative Science Quarterly*, **41**, pp. 116–145.

Predicast (various years). *F&S Index of Corporate Change*. Predicast, Inc. Cleveland, OH.

Roberts, K. and M. Weitzman (1981). 'Funding criteria for research, development, and exploration projects', *Econometrica*, **49**, pp. 1261–1288.

Stinchcombe, A. L. and C. A. Heimer (1985). *Organization Theory and Project Management*. Norwegian University Press, London.

Teece, D. J. (1992). 'Competition, cooperation, and innovation: Organizational arrangements for regimes of rapid technological progress', *Journal of Economic Behavior and Organization*, **18**(1), pp. 1–25.

Trigeorgis, L. (1991). 'Anticipated competitive entry and early preemptive investment in deferrable projects', *Journal of Economic Business*, **43**, pp. 143–156.

U.S. Board of Governors of the Federal Reserve System (1984–1993). *Federal Reserve Bulletin*, *70–78*. U.S. Government Printing Office, Washington, DC.

U.S. Congress Joint Economic Committee (1984–1993). *Economic Indicators*. U.S. Government Printing Office, Washington, DC.

U.S. Department of Commerce (1984). *High-technology Industries: Profiles and Outlooks—Biotechnology*. International Trade Administration, Washington, DC.

Williamson, O. E. (1985). *The Economic Institutions of Capitalism*. Free Press, New York.

Williamson, O. E. (1988). 'Technology and transaction cost economics: A reply', *Journal of Economic Behavior and Organization*, **10**, pp. 355–363.

Williamson, O. E. (1991). 'Comparative economic organization: The analysis of discrete structural alternatives', *Administrative Science Quarterly*, **36**, pp. 269–296.

APPENDIX

The index composition varies over time, that is, stocks are added to and deleted from the index. Therefore, an adjustment, similar to that applied to the NASDAQ Composite Index, is needed to account for its varying composition over time. Since stocks may enter at times other than $t = 0$, the reference will be to the entry time of each stock as it enters the index. The price ratio in equation (3) becomes P_{it}/P_{ie}. At any time a new security is added, say at $t+$, which is an instant after the close of period $t-$, the adjustment is changed as follows:

$$B_0 \frac{A_{t+}}{N+1} \sum_{i=1}^{N+1} \left(\frac{P_{it}}{P_{ie_i}}\right) = I_{t+} = I_t = B_0 \frac{A_t}{N} \sum_{i=1}^{N} \left(\frac{P_{it}}{P_{ie_i}}\right) \quad \text{(A1)}$$

where, N is the number of firms in the index ($N = 9$). It is helpful to think of $A_t/(N+1)$ as an 'index divisor.' Thus, the left-hand side of this expression can be written as:

$$\frac{B_0}{D_{t+}} \sum_{i=1}^{N+1} \left(\frac{P_{it}}{P_{ie_i}}\right) = I_{t+}, \text{ where } D_{t+} = \frac{N+1}{A_{t+}} \quad \text{(A2)}$$

The index divisor can be calculated directly as:

$$D_{t+} = \frac{B_0}{I_t} \sum_{i=1}^{N+1} \left(\frac{P_{it}}{P_{ie_i}}\right) \quad \text{(A3)}$$

The index value, I_t, was adjusted for inflation using a monthly measure of the Consumer Price Index (CPI) for all items as published in *Economic Indicators* (U.S. Congress Joint Economic Committee, 1984–1993). The formula for the inflation adjustment to I_t is the following:

$$\text{Inflation adjusted } I_t = I_t \times \frac{CPI_{t=0}}{CPI_t} \quad \text{(A4)}$$