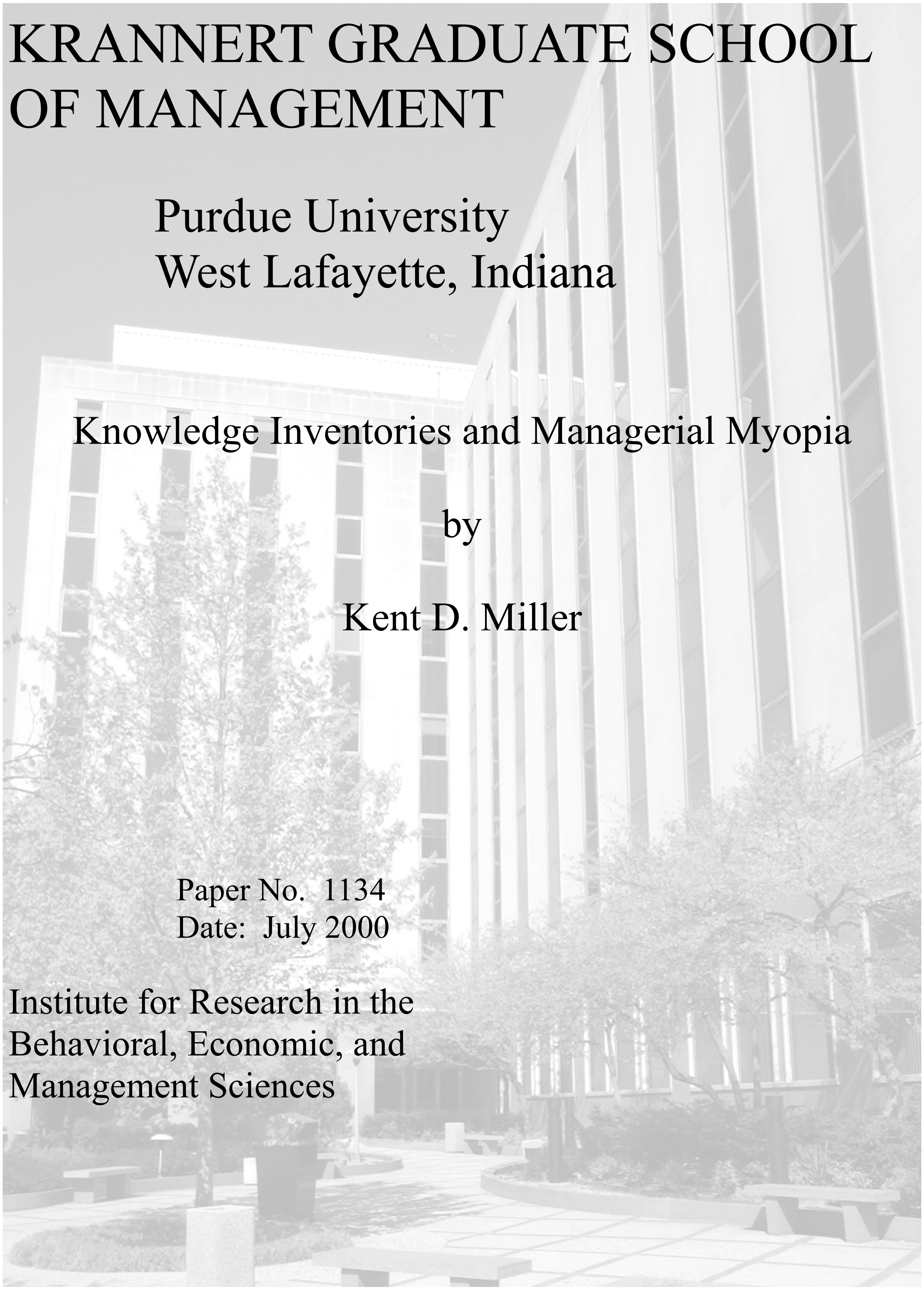

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## Knowledge Inventories and Managerial Myopia

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# KNOWLEDGE INVENTORIES AND MANAGERIAL MYOPIA

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## KNOWLEDGE INVENTORIES AND MANAGERIAL MYOPIA

Managing knowledge inventories is the central issue posed by the knowledge-based view of the firm. Because of future opportunities to switch among technologies and idle or deploy technologies over time, managing knowledge inventories requires valuing flexibility. Real option theory presents normative pricing formulas for valuing flexibility. These formulas assume managers consider the full time horizon of technologies as well as all available substituting and complementary technologies. This study considers the implications of violations of these assumptions (i.e., temporal and spatial myopia) for managers' technology investment decisions. Specifying decision criteria under alternative forms of myopia suggests possible sources and patterns of technology investment decision errors.

The starting point for this research is the challenge of "maintaining appropriate knowledge inventories" recognized by Levinthal and March (1993). They described the "knowledge inventory" of a firm as "a small number of specialized competencies maintained by the individuals and groups that make up the organization" (p. 103). Managing knowledge inventories is problematic: "[w]here situations or proper responses are numerous and shifting, it is harder to specify and realize optimal inventories of knowledge. By the time knowledge is needed, it is too late to gain it; before knowledge is needed, it is hard to specify precisely what knowledge might be required or useful. It is necessary to create inventories of competencies that might be used later without knowing precisely what future demands will be" (p. 103).

In taking on the challenge of managing knowledge inventories, we are adopting the view of firms as bundles of competencies. Research from the "knowledge-based" view of the firm has elaborated this perspective. Leonard-Barton (1992) provides a broad conceptualization of the knowledge set of the firm, encompassing: (1) employee knowledge and skills, (2) technical systems, (3) managerial systems, and (4) values and norms. Resource-based (e.g., Barney, 1991) and dynamic capabilities (Teece, Pisano, & Shuen, 1997) views on organization and competitive advantage broadly overlap with the knowledge-based perspective.

Independent of research on the knowledge-based view of the firm, a distinct stream of research in finance has addressed the question of the value to organizations of holding multiple substituting technologies. Kulatilaka and Marcus (1988), Kulatilaka and Trigeorgis (1994), and Kulatilaka (1995) derived option values for state-contingent switching among alternative technologies. Drawing from that research, this study frames the question of managing knowledge inventories in terms of the parameters identified in real options research. Although the real options approach is a helpful way to frame the problem of managing knowledge inventories, the decision rules offered in that research make unrealistic assumptions about managerial foresight (Chi & Fan, 1997). Real options research emphasizes normative decision rules that assume away many practical problems and managers' own limitations (Lander & Pinches, 1998).

This study introduce managerial myopia into the real options perspective on technology investment and switching decisions. Myopia takes two forms. Levinthal and March (1993) and Kogut and Kulatilaka (1994) suggested temporal myopia (i.e., focusing on the short-term) makes managers unaware of the full option value associated with their investments. Levinthal and March (1993) added spatial myopia (i.e., the lack of awareness of other technology alternatives available within the organization) to our concerns about managerial myopia. Alternative forms of myopia reflect different assumptions about the boundedness of managerial rationality. In the extreme, managers are unable to identify the current state, making technology selection problematic. Alternatively, firms may be able to identify the state of the world in any given period but not future states. Their decisions may reflect limited foresight or knowledge of alternative technologies available within the organization. These differing assumptions result in unique behavioral implications for knowledge inventory management.

This paper draws from real options research to clarify the knowledge inventory problem. However, departing from previous real options research, we explore the implications of managerial myopia for knowledge inventory management. The first section introduces the real option approach to technology acquisition and deployment. The following section presents three forms of temporal myopia and their implications for knowledge inventory management. We then turn to the implications of spatial myopia—in isolation and in combination with temporal myopia. Throughout the paper, we elaborate the types of technology investment errors that are likely to arise as a result of temporal and spatial myopia. The paper's final section discusses the major findings and implications for future research.

## OPTION APPROACH TO TECHNOLOGY ACQUISITION AND SWITCHING

The knowledge inventory problem involves decisions about the firm's portfolio of technologies. Uncertainty complicates this problem. If technology investments require sunk costs and extended time horizons, the decision is nontrivial. Managers cannot costlessly reverse current decisions if the state of the world changes. Rather, they face disposal or on-going maintenance costs if technologies are idle. Further complicating this problem is the possibility that some technologies may be available for only a short time and if not acquired during the window of opportunity become inaccessible. Such situations characterize "technology races," where firms that delay are locked out of subsequent investments because of competitors' aggressive moves into new technologies.

We begin with a simple version of the problem of technology acquisition under uncertainty. The managers of a new start-up firm must decide the composition of their knowledge inventory given two available technologies. These alternatives may involve differing inputs and/or outputs. To keep the problem simple, we assume the technologies are substitutes. The performance characteristics of the two technologies are such that they would never be implemented together. There are many examples of such technology choices. A firm may choose between two alternative energy sources (e.g., gas or coal), two alternative designs (e.g., electronic or mechanical), or two alternative suppliers (e.g., domestic or foreign). On the output side, the technology alternatives involve knowledge of different product and geographic markets. For example, firms may switch between alternative customer groups or distribution channels.

Incorporating both technologies into the firm's knowledge inventory presents opportunities to switch technologies over time, thus enhancing organizational flexibility. In any given period, one technology is implemented, while the other remains a latent possibility for future deployment. The value of purchasing a substituting technology depends not only on the characteristics of the technologies themselves, but also on the probability of future shifts in the state of the world. If the relative prices of inputs and customer demands are constant, then purchasing an alternative technology is an unnecessary expense. A single technology would be optimal in all periods. However, possessing an alternative technology may add value under uncertainty. This value can be expressed in terms of the value of the option to switch among technologies.

We consider a simple two-state, two technologies model as a starting point for understanding the management of knowledge inventories. In this model, the value of the cash flows associated with alternative technologies, $k \in (1, 2)$, depend on a stochastic state variable, $S_t \in (1, 2)$, in period $t$. Hence, $R_k(S_t)$ designates the revenues accruing to the firm when the technology embodying knowledge $k$ is used and state $S$ prevails in period $t$. Furthermore, let $c_{12}$ indicate the cost of switching from technology $1$ to $2$, the alternative. Such costs are avoided if the firm makes no changes in its operating technology over time. Hence, if the firm operated with technology $1$ in period $t$, it may continue with the same technology in the subsequent period, $t+1$, and realize revenues of $R_1(S_{t+1})$ or switch to the alternative technology to realize the net revenue $R_2(S_{t+1})$-$c_{12}$.

The insight that the problem of managing knowledge inventories requires option theoretic decision making allows us to build on existing research on real options. Finance research on real options has addressed the problem just described. Kulatilaka and Marcus (1988) and Kulatilaka and Trigeorgis (1994) examined versions of this problem with just three decision points: an initial technology choice, followed by two opportunities to switch technologies or maintain the existing technology in use. Kulatilaka (1995) generalized this approach for any finite number of alternative technologies and any finite time horizon. Each of these articles assumed the firm already possessed both technologies and did not examine the initial technology acquisition decision. Here we consider both the initial technology acquisition and subsequent technology deployment.

If the firm purchases just one technology for implementation in all future periods, traditional discounted cash flow analysis can be used to compute the expected value of the firm.[1] Label the present value of implementing technology $k$ as $V_k$ and the associated initial sunk investment cost as $I_k$. Because purchasing a single technology involves an inflexible position, the standard NPV approach using risk-adjusted discount rates can be used to derive $V_1$ and $V_2$.

Because of the flexibility associated with holding both technologies, deriving the value of this knowledge inventory, $V_{12}$, requires a solution approach that differs from standard NPV analysis. Assuming the firm is able to derive the values of the alternative technology holdings, its valuation based on an optimal investment strategy is given by $\max[V_1-I_1, V_2-I_2, V_{12}-I_1-I_2, 0]$.

In order to solve for the value of obtaining both technologies, $V_{12}$, management must specify the intended strategy of technology deployment. When purchasing both technologies, optimal behavior requires choosing a current technology to maximize the present value of discounted expected future revenues net of switching costs over the entire period of operation. Let $F_t(S_t)$ denote the present value at $t$ (using the interest rate, $r$) of net profit flows assuming optimal behavior in each period up to the final period, $T$.[2] For a firm holding both technologies, its initial technology choice is found by solving:

$$F_0(S_0) = max[R_1(S_0), R_2(S_0)] + E_0[F_1(S_1)]/(1+r). \tag{1a}$$

If the firm arrives at time $t$ operating with technology $1$ in state $S_t$, its technology choice is the solution to:

$$F_t(S_t) = max[R_1(S_t), R_2(S_t)-c_{12}] + E_t[F_{t+1}(S_{t+1})]/(1+r). \tag{1b}$$

Several implications for optimal knowledge inventories flow from this model. First, if a single technology dominates the other in all possible states, there is no value added from acquiring the alternative technology. Hence, for both technologies to be acquired, it must be that the optimal technology differs with the state of the world, i.e., $R_1(S_t=1) > R_2(S_t=1)$ and $R_2(S_t=2) > R_1(S_t=2)$. Second, the higher the switching costs, the lower the value associated with holding an alternative technology. Third, in the absence of switching costs ($c_{12}=c_{21}=0$), optimizing equation (1b) is straightforward. The firm simply chooses the technology maximizing current period cash flows and does not need to consider the future. In the absence of switching costs, equations (1a) and (1b) simplify to $\max[R_1(S_t), R_2(S_t)]$, and the possibility of a future state shift has no effect on the technology implemented. However, with switching costs, looking forward all the way to the final period $T$ is the only way to derive an optimal pattern of technology deployment decisions.

Levitt and March (1988) and Garud and Nayyar (1994) alert us to the possibility that inactive technologies require on-going investments for their maintenance. Consider the four dimensions of knowledge identified by Leonard-Barton (1992): (1) employee knowledge and skills, (2) technical systems, (3) managerial systems, and (4) values and norms. Each of these knowledge storehouses is susceptible to deterioration or loss if neglected. Required maintenance investments may be in physical assets embodying a technology, employee training and socialization, or in refreshing organizational systems and routines. Garud and Nayyar (1994) point out that the more tacit and complex the knowledge, the greater the investments needed for maintenance and reactivation.

If we allow that there is a positive maintenance cost $m_k$ that must be incurred each period in order to retain the inactive technology alternative $k$, the modifications to valuing a firm holding both technologies are straightforward. Once again, we have a dynamic programming problem that in the initial period takes the form:

$$F_0(S_0) = max[R_1(S_0)-m_2,\ R_2(S_0)-m_1] + E_0[F_1(S_1)]/(1+r). \quad (2a)$$

where $E_0[\cdot]$ is the expectation at period 0. Operating with technology $1$ in state $S_t$ at time $t$, its technology choice is the solution to:

$$F_t(S_t) = max[R_1(S_t)-m_2,\ R_2(S_t)-c_{12}-m_1] + E_t[F_{t+1}(S_{t+1})]/(1+r). \quad (2b)$$

Hence, the presence of maintenance costs provides an augmented pair of criteria for evaluating whether to acquire and retain both technologies in the firm's knowledge inventory.

As specified here, the optimal solution to the firm's dynamic programming problem requires working backward from the terminal period to the present period. Real options research details this solution approach. Kulatilaka (1995) applied this recursive solution technique. Dixit and Pindyck (1994: ch. 4) provided mathematical details for applying dynamic programming techniques to value real options.

Our interest here is not in the well-documented details of the dynamic programming approach to derive the optimal solution to the specified problems. Rather, we want to challenge the assumptions about managerial decision making underlying the available solution technique. The dynamic programming solution requires that firms optimize by taking into consideration the full time horizon in a multiperiod model. The alternative view, presented by Levinthal and March (1993) and Laverty (1996), is that managers are subject to temporal myopia, i.e., they are short-sighted. Furthermore, the dynamic programming solution assumes all alternative technologies are taken into consideration when making investment decisions. However, managers may consider technology alternatives sequentially or in subsets (March, 1994). Such approaches miss the optimization opportunities associated with the full set of available technologies.

We now turn our attention to the implications of temporal myopia for technology acquisition and switching decisions over time. After that, we take up the problem of considering technology acquisition decisions in isolation, a form of "spatial myopia."

## TEMPORAL MYOPIA

The foresightfulness of management is a critical determinant of technology investment decisions. This recognition has led some to criticize managers for their short-term orientation. Laverty (1996) distinguished several causes for "economic short-termism": (1) flawed management practice (such as capital budgeting criteria favoring short-term performance), (2) managerial opportunism, (3) stock market myopia, (4) fluid and impatient capital, and (5) information asymmetry (between management and capital markets). Only the first two of these reflect shortcomings of management. The others reflect capital market imperfections.

In addition to these explanations for "economic short-termism," there may be an even more fundamental cause related to the cognitive limitations of managers. Bounded rationality limits the alternatives managers consider (March & Simon, 1958) and results in sequential attention to goals (Cyert & March, 1963; Cohen, March, & Olsen, 1972). Cognitive limits force management to allocate attention between current and future considerations (Levinthal & March, 1993). Pressing current organizational problems are the most salient motivators of organizational search, not future-oriented considerations. This study follows in the tradition of Simon, March, and Cyert (March & Simon, 1958; Cyert & March, 1963). We start with the observation that the rationality of managers is bounded, limiting the scope of alternatives and time periods considered when making technology acquisition decisions. Myopia follows from these cognitive limitations. We need not assume opportunism nor incentives incompatible with long-term shareholder wealth maximization to motivate our topic.

The degree to which managers are myopic is an open question. Myopia may vary across management teams and decision contexts (Ocasio, 1997). Differences in the extent of myopia across firms contribute to differential expectations and, in turn, differences in performance (Barney, 1986). Here we consider three different forms of myopia: (1) the extreme case of inability to discern the current state, (2) ability to discern the current state but no consideration of the future, and (3) limited, single-period foresight. This section elaborates decision rules under each of these forms of myopia.

**Uncertainty about the Current State**

Consider the extreme form of temporal myopia in which managers cannot categorize the current state. Even the probabilities of alternative states cannot be updated on the basis of currently available information. If we allow that managers know the state variable ex post, inability to update current state probabilities occurs only if $Pr(S_t=1 \mid S_{t-1}) = Pr(S_t=1)$ and $Pr(S_t=2 \mid S_{t-1}) = Pr(S_t=2)$. That is, the conditional probability of a state given the previous state is the same as the unconditional probability. Heiner (1983) argued that such uncertainty gives rise to predictable behavior. It is not hard to show why this is the case. Predictability results because managers are unable to make state-contingent alterations in the way they do business.

Under uncertainty about the current state, the firm simply chooses the technology that maximizes its expected payoff. They choose technology 1 if:

$$Pr(S_t=1)R_1(S_t=1)+ Pr(S_t=2)R_1(S_t=2)-I_1 > Pr(S_t=1)R_2(S_t=1)+ Pr(S_t=2)R_2(S_t=2)-I_2 \quad (3)$$

and the expected payoff is positive. In this case, the knowledge inventory consists of a single technology. The firm uses this same technology in all periods and no switching occurs. Managers make a single technology acquisition and deployment decision based on maximizing expected returns, but can add no additional value over time due to their inability to make state-contingent decisions.

Analyzing the case of uncertainty about the current state yields an important qualifier for technology options to have positive values. Real option value derives from the ability to defer state-contingent decisions until the state is known or, at least, further information clarifying the probabilities of alternative states is known. Firms that are unable to discern the current state must at least have conditional state probabilities (based on the previous state) that differ from the unconditional probabilities in order to realize some option value from technological flexibility. There is no option value when the commitment to deploy a technology must be made prior to receiving information that either reveals the current state or allows updating of the possible state probabilities.

Assuming (3) holds, and technology 1 is acquired, the firm should realize a gain. The initial investment, $I_1$, occurs only once and there are no switching or storage costs in subsequent periods because the firm holds no alternative technology, and has no incentive to idle the chosen technology. The longer the time horizon (T), the more remote becomes the possibility of a Type I error. Type I errors occur when technologies are deployed that result in losses for the firm (Shapira, 1995). Much more likely are Type II errors—failures to make investments that would be profitable to the firm. This occurs when, due to the one-time initial investment cost, the firm rejects a technology that would be profitable over the time horizon (T).

**Clarity about Current State, but No Foresight**

Alternatively, if managers are able to ascertain the current state but fail to consider the future, they will simply choose the technology that maximizes current returns for the identified state. As the firm begins operating, it will acquire the technology that offers the highest payoff, given the current state. Management selects the technology $k$ that maximizes $R_k(S_0)-I_k$. Because management neglects all future periods, they do not acquire the alternative suboptimal technology, even if foregoing the alternative technology precludes its acquisition in the future. If the firm selects technology 1, its payoff in the subsequent period is $R_1(S_1=1)$ if state 1 continues. If state 2 occurs and technology 2 is no longer available, the firm realizes $\max[R_1(S_1=2), -m_1]$, where $m_1$ is the maintenance cost associated with idling technology 1 for a period.[3] If technology 2 remains available and $R_2(S_t=2)-I_2-c_{12}-m_1 > max[R_1(S_t=2), -m_1]$, the firm will acquire technology 2 when state 2 occurs. With management's focus exclusively on the current period, the initial technology acquisition decision and the subsequent decision to acquire the alternative technology overlook future maintenance costs.

Because of maintenance costs, technology acquisition decisions are path dependent. The first technology chosen raises the required return for the alternative technology. It is possible that $I_2+c_{12}+m_1 > R_2(S_t=2) > I_2$. In this situation the occurrence of state 1 in the initial period locks the firm into technology 1 from that point forward (despite the desirability of technology 2 if state 2 had occurred initially). This points out how temporal myopia, in combination with maintenance and switching costs, can limit the breadth of knowledge inventories (i.e., organizational flexibility). Unwillingness to invest in alternative technologies may evidence temporal myopia rather than lack of awareness of alternatives (i.e., spatial myopia). Due to temporal myopia, the state in the first period can have a disproportionate influence (relative to the nonmyopic case) on technology choice and performance throughout the life of the firm.

If both technologies have been acquired, technology switching occurs only if:

$$R_2(S_t=2)-R_1(S_t=2) > c_{12}+(m_1-m_2) \tag{4a}$$

and

$$R_1(S_t=1)-R_2(S_t=1) > c_{21}+(m_2-m_1) \tag{4b}$$

In words, the sum of the switching and incremental maintenance costs must be less than the increment to revenue associated with shifting to the ideal technology for the current state. If the inequalities in (4a) and (4b) are reversed, the firm will lock into a single technology for its duration.

If abandonment costs exceed maintenance costs, then previously acquired technologies will be retained. When the firm only considers the present state and is not forward looking, its technology acquisition decisions consider the maintenance cost of idling existing technologies but not the future costs of idling the technology it is currently acquiring. In contrast with the dynamic programming approach, temporal myopia results in inattention to the probability of a state change in the future and neglect of the future switching cost associated with reversing the present technology choice. This increases the possibilities for Type I errors relative to decision making under uncertainty about the current state, where only a single technology is acquired.

**Limited Foresight**

Also of interest to us is the situation in which managers are able to discern the current state prior to making current technology deployment decisions and they are foresightful—but only limitedly so. A simple way to model this assumes managers look ahead a single period. They formulate expectations regarding the next period state conditional on the current state. Under this form of temporal myopia, at the initial time 0, an organization will acquire technology 1 in state 1 if its expected two-period return is positive:

$$R_1(S_0=1)-I_1+[Pr(S_1=1 \mid S_0=1)R_1(S_1=1)+ Pr(S_1=2 \mid S_0=1)R_1(S_1=2)]/(1+r) > 0 \tag{5}$$

and exceeds that of technology 2.[4] That is,

$$R_1(S_0=1)-I_1+[Pr(S_1=1 \mid S_0=1)R_1(S_1=1)+ Pr(S_1=2 \mid S_0=1)R_1(S_1=2)]/(1+r) >$$

$$R_2(S_0=1)-I_2+[Pr(S_1=1 \mid S_0=1)R_2(S_1=1)+ Pr(S_1=2 \mid S_0=1)R_2(S_1=2)]/(1+r)$$

or, rearranging terms,

$$R_1(S_0=1) - R_2(S_0=1) + \{Pr(S_1=1 \mid S_0=1)[R_1(S_1=1)-R_2(S_1=1)]$$

$$+Pr(S_1=2 \mid S_0=1)[R_1(S_1=2)-R_2(S_1=2)]\}/(1+r) > I_1-I_2. \tag{6}$$

In words, if the increment (relative to the alternative technology) to current revenue plus discounted expected revenue in the next period exceeds the incremental investment cost, then purchase technology 1. Otherwise, purchase technology 2.

It is interesting to note that when considering the first technology to adopt, the cost of switching away from that technology does not factor into the investment decision. This is an implication of sequential investment decision making. The cost of switching away from the initial technology, $c_{12}$, is absent from both (5) and (6).

If the firm must also decide whether to acquire technology 2 (at time 0 in state 1), its decision is guided by the following criterion, which anticipates maintenance costs in the current and coming period:

$$Pr(S_1=2 \mid S_0=1)[R_2(S_1=2)-R_1(S_1=2)-c_{12}-m_1]/(1+r) > I_2+[1+Pr(S_1=1 \mid S_0=1)/(1+r)]m_2 \tag{7}$$

Comparing (5) and (7), we see that the presence of maintenance and switching costs raises the required return for the second-best technology relative to what it would be if the firm had not already acquired another technology. Both the maintenance costs on the existing technology and the technology under consideration raise the required return. Whereas the cost of switching away from the initial technology was irrelevant when considering its purchase, this cost decreases the likelihood of acquiring a subsequent technology. This is another indication of the path-dependency effect noted earlier.

If the decision regarding technology 2 can be postponed until a time $t$ in the future when state 2 occurs, then at $t$, management will consider whether:

$$R_2(S_t=2)-I_2-c_{12}-m_1+\{Pr(S_{t+1}=2 \mid S_t=2)[R_2(S_{t+1}=2)-m_1]-Pr(S_{t+1}=1 \mid S_t=2)(m_2+c_{21})\}/(1+r)$$

$$>R_1(S_t=2)+Pr(S_{t+1}=2 \mid S_t=2)R_1(S_{t+1}=2)+Pr(S_{t+1}=1 \mid S_t=2)R_1(S_{t+1}=1)/(1+r). \tag{8}$$

This decision rule assumes the firm will subsequently revert back to using technology 1 when state 1 occurs. Comparing equations (7) and (8) indicates that being able to postpone investment in the alternative technology adds value relative to the now-or-never scenario requiring a decision on both technologies at $t=0$. When investments can be postponed, the avoidance of maintenance costs on the idle technology enhance firm value.[5]

Under what conditions will a firm switch back and forth between the two technologies? Once the firm has a knowledge inventory consisting of both technologies, it will follow a pair of decision rules regarding switching. Using technology 1 in the previous period, $t-1$, it will switch to technology 2 in state 2 at $t$ if:

$$R_2(S_t=2)-c_{12}-m_1+\{Pr(S_{t+1}=1\,|S_t=2)[R_1(S_{t+1}=1)-c_{21}-m_2]+Pr(S_{t+1}=2\,|S_t=2)[R_2(S_{t+1}=2)-m_1]\}/(1+r)$$

$$> R_1(S_t=2)-m_2+\{Pr(S_{t+1}=1\,|S_t=2)R_1(S_{t+1}=1)+Pr(S_{t+1}=2\,|S_t=2)R_1(S_{t+1}=2)-m_2\}/(1+r). \quad (9)$$

The expression to the left of the inequality reflects the current period and discounted expected subsequent period revenue allowing for switching from technology 1 to technology 2, and switching back. The right-hand side of the inequality reflects the current revenue and discounted expected revenue associated with staying with technology 1 and keeping technology 2 idle. Rearranging terms, we can simplify (9) as:

$$[R_2(S_t=2)-R_1(S_t=2)-c_{12}-(m_1-m_2)]+Pr(S_{t+1}=2\,|S_t=2)[R_2(S_{t+1}=2)-R_1(S_{t+1}=2)-(m_1-m_2)]/(1+r)$$

$$> Pr(S_{t+1}=1\,|S_t=2)c_{21}/(1+r). \quad (10)$$

Decision rule (10) also assumes that once operating in technology 2, the firm will switch to technology 1 when the state reverts to state 1 at time t.[6] Expression (10) indicates the firm will shift from one technology to the other when the increment to current revenues and discounted expected revenues exceeds the discounted expected reverse switching cost.[7] The difference in maintenance costs ($|m_1-m_2|$), rather than the levels of maintenance costs, affects the switching decision.

The problem addressed in this section involves the simplest possible knowledge inventory decision. We allowed for only two substituting technologies and two possible states. We also considered only limited—single-period—foresightfulness. Despite this intentional simplicity, the resulting decision rules regarding acquiring and deploying technologies are rather complex. The complexity of expressions (10) presents a prima facie case that firm technology deployment decisions follow decision rules that either neglect the future, as with (4a) and (4b), or exhibit very limited foresight. It seems unlikely that firms follow more sophisticated decision rules arising with $n$-period foresight ($n>1$), much less the sophisticated optimization approaches represented by the nonmyopic dynamic programming approach to real option valuation.

**Summary**

The three forms of temporal myopia predict distinct investment behaviors. Under uncertainty about the current state, there is no option value associated with acquiring an alternative technology. The firm locks into the single technology with the highest expected value. Type I errors are unlikely. Error of omission (type II) occur frequently.

With clarity about the current state but no attention to the future, investment decisions become path dependent. The arbitrary order of occurring states can have important implications for knowledge inventories. The initial state may lock the firm into a technology that, over the long-run, underperforms the alternative. Neglect of future maintenance and switching costs can produce type I errors.

With limited foresight, investment decisions are still path dependent. However, the path dependency is not as dramatic as in the absence of attention to the future. The greater the foresight, the greater the extent to which future maintenance and switching costs factor into initial investment decisions. As foresight increases, the less likely are both type I and type II errors. However, technology acquisition and switching decision rules become quite complex as we expand the time horizon considered by management.

## SPATIAL MYOPIA

A second form of myopia identified by Levinthal and March (1993) is the tendency to overlook distant places, or "spatial myopia." One expression of spatial myopia is the lack of awareness of technologies existing elsewhere within the firm. Constraints on managers' attention and intraorganizational boundaries cause spatial myopia. For example, one division may be unaware of the new technologies developed in another division. Limited attention must be allocated across many competing projects resulting in sequential rather than holistic appraisal of available alternatives (March & Simon, 1958).

Kahneman and Lovallo (1993) portrayed managers as considering investment decisions singularly rather than evaluating them in light of the firm's overall portfolio (see also Bercovitz, de Figueiredo, & Teece, 1997). They labeled the resulting biases "isolation errors." They argued that managers overlook portfolio effects when assessing project risk, resulting in exaggerated risk perceptions. In the real options literature, we find a similar contention. Hurry (1994) indicated that organizations may possess unrecognized "shadow options."

For theoretical treatment, it is useful to distinguish spatial and temporal myopia. In practice, they may have similar implications for knowledge inventories. As noted earlier, short-sightedness can reduce the range of technologies adopted into the firm's knowledge inventory. Under temporal myopia, incumbent technologies are more attractive than new alternatives requiring large initial sunk investments. Such path dependencies, lock firms into repeated use of an established technology. This neglect of alternative technologies looks like spatial myopia but actually evidences temporal myopia.

In order to better understand spatial myopia, we begin by considering it in isolation from temporal myopia. We then consider managerial decisions combining both spatial and temporal myopia.

Spatial myopia involves managerial oversight regarding potential interactions among technologies when deployed at the same time. These technologies are neither mutually exclusive nor are their payoffs independent. Consider two technologies, $k \in (1, 2)$, that exist within the same firm and have initial investment costs $I_k$. These technologies may be complements or substitutes. As before, the revenues, $R_k(S_t)$, depend on the stochastic state variable, $S \in (1, 2)$.

The firm incurs a maintenance cost, $m_k$, during each period in which technology $k$ remains idle. The firm incurs a cost $c_k$ when it redeploys technology $k$ after it has been idle.

**Foresightful Solution**

If managers experience spatial myopia but not temporal myopia, their approach to valuing a technology is similar to the dynamic programming problem presented earlier. Flexibility comes from state-contingent decisions regarding deploying or idling individual technologies, rather than switching among alternative technologies. Kulatilaka and Trigeorgis (1994) and Kulatilaka (1995) discussed the correspondence between these two types of decisions and their optimal solution approach. The flexibility to shut down and restart a project adds option value. Kulatilaka's (1995) solution generalizes earlier work by McDonald and Siegel (1985).

Let $F_k(S_t)$ denote the present value at $t$ (using the interest rate, $r$) of net profit flows from technology $k$ assuming optimal behavior in each period up to the final period, $T$. With nonmyopic foresight, the value of technology $k$ at the time of initial investment is:

$$F_k(S_0) = \max[R_k(S_0), 0] + \mathrm{E}_0[F_k(S_1)]/(1+r). \qquad (11a)$$

If faced with a now-or-never decision, the firm invests if $F_k(S_0) > I_k$. If the technology is operating at time $t$ in state $S_t$ its technology choice is the solution to:

$$F_k(S_t) = \max[R_k(S_t), -m_k] + \mathrm{E}_t[F_k(S_{t+1})]/(1+r). \qquad (11b)$$

If the technology is idle, upon arriving at time $t$ its value from that point on is:

$$F_k(S_t) = \max[R_k(S_t)-c_k, -m_k] + \mathrm{E}_t[F_k(S_{t+1})]/(1+r). \qquad (11c)$$

With nonmyopic foresight, this problem would be solved recursively. Based on independent assessments of each technology, the firm may employ both technologies, just one of the technologies, or neither technology at time t. The resulting knowledge inventory is perceived as the best set of technologies under spatial myopia. However, despite nonmyopic foresight, this solution neglects potential interactions among technologies affecting future returns.

If both technologies are implemented simultaneously, interactions may occur. Designate the realized revenues, $\hat{R}_k(S_t)$, to distinguish them from the stand-alone revenues, $R_k(S_t)$. If the effect of implementing these two technologies simultaneously results in a positive (i.e., synergistic) interaction, we have $\hat{R}_1(S_t)+\hat{R}_2(S_t)>R_1(S_t)+R_2(S_t)$. This condition places no constraint on whether the revenue for any one technology, $\hat{R}_k(S_t)$, will exceed the spatially-myopic expectation, $R_k(S_t)$. Implementing both technologies simultaneously may benefit the returns to one technology to the detriment of the other, yet the total effect may still add value to the company.

Alternatively, simultaneous deployment may harm firm performance. Using more than one technology may produce detrimental competition for internal resources or their products may compete for sales. In this case, the relationship between actual revenues and the spatially myopic expectation is $\hat{R}_1(S_t)+\hat{R}_2(S_t)<R_1(S_t)+R_2(S_t)$. The returns to one or both technologies are negatively affected by the presence of the other technology. This arises when technologies are substitutes rather than complements.

Given two possible technologies and two possible states of the world, there are four possible outcomes regarding technology acquisitions for the spatially myopic firm. These outcomes relate to the decision criterion (11a) and assume all technology acquisition decisions must be made at the beginning period, $t$=0. First, $F_k(S_0)>I_k$ could hold for both technologies. The second and third possibilities involve this condition holding for one technology but not the other. Fourthly, $F_k(S_0)<I_k$ could hold for both technologies. Each of these cases presents potential deviations from the decisions that would be made in the absence of spatial myopia. For comparison, let $\hat{F}_k(S_t)$ designate the valuation of technology $k$ comparable to equation (11a) but using non-myopic revenue projections.

The first situation, in which $F_k(S_0)>I_k$ holds for both technologies, is not problematic for synergistic technologies. Both technologies would be acquired with or without spatial myopia.

The only distortion is that actual revenues will exceed projections. In the case of incompatible technologies, the spatially-myopic firm may overinvest. This occurs if:

$$\hat{F}_1(S_0)+\hat{F}_2(S_0)-I_2<F_1(S_0) \text{ or } \hat{F}_1(S_0)+\hat{F}_2(S_0)-I_1<\hat{F}_2(S_0). \tag{12a}$$

These conditions result in a Type I technology investment errors.

The two intermediate cases occur when one technology is purchased but not the other. For nonsynergistic technologies, the spatially myopic firm still makes the best possible choice. However, for synergistic technologies, the spatially-myopic decision to purchase only technology $k$ is suboptimal if:

$$\hat{F}_1(S_0)+\hat{F}_2(S_0)-(I_1+I_2)>F_k(S_0)-I_k. \tag{12b}$$

These conditions result in Type II errors.

The fourth situation, in which neither technology is purchased, is straightforward. For nonsynergistic technologies, there is no distortion from the technology investment that would be made in the absence of spatial myopia. For synergistic technologies, the spatially-myopic firm may underinvest. This occurs when:

$$\hat{F}_1(S_0)+\hat{F}_2(S_0)-I_2>F_1(S_0) \text{ and } \hat{F}_1(S_0)+\hat{F}_2(S_0)>I_1+I_2$$

or, $$\hat{F}_1(S_0)+\hat{F}_2(S_0)-I_1>F_2(S_0) \text{ and } \hat{F}_1(S_0)+\hat{F}_2(S_0)>I_1+I_2. \tag{12c}$$

These conditions produce Type II errors.

**Combining Spatial and Temporal Myopia**

What patterns of decisions would we expect when both forms of myopia occur simultaneously? In this section, we maintain the assumption of spatial myopia and reintroduce temporal myopia. We begin by discussing the firm focused on the current state and then examine single-period foresight.

**Clarity about current state, but no foresight.** Assume managers only consider the current period and also suffer from spatial myopia. Their initial technology investment decisions turn on whether the perceived value of a technology's single-period revenue exceeds its investment cost, i.e., whether $R_k(S_t) > I_k$.. With two available technologies, there are four possible outcomes to consider. The first case is when neither technology would be implemented in either state. The second case is when one technology would be implemented in one state and the other technology in the other state. The other two cases involve simultaneous deployment of technologies in one or both states of the world.

The possible technology errors in the first case are quite straightforward. Management perceives the firm as technologically-impoverished with $R_k(S_t) < I_k$ for $k$=1,2 and $S_t$=1,2. This case results in (Type II) distortions from the non-myopic case if extending the time horizon out to the terminal period $T$ and allowing for technology interactions results in

$\hat{F}_1(S_t) + \hat{F}_2(S_t) > I_1 + I_2$.

In the second case, one technology is implemented in one state of the world and another in the other state. Because of this pattern of technology deployment, there is no discrepancy between expected and realized revenues. As such, there can be no Type I errors attributable to spatial myopia. For synergistic technologies, spatial myopia could produce Type II errors. As long as technology maintenance ($m_k$) and reactivation costs ($c_k$) are not excessive, temporal myopia results in a systematic downward bias in perceived technology values and, as such, will not cause Type I errors. The most likely errors are those of omission (Type II) due to temporal myopia and, in the case of synergistic technologies, spatial myopia.

The other two possible situations involve simultaneous deployment of technologies in one or both states. These create possible mismatches between expected and realized revenues for the spatially-myopic firm. Both type I and type II technology errors are possible. A type I error occurs when:

$R_k(S_t) > I_k$ for $k$=1,2

and $\hat{F}_1(S_t) + \hat{F}_2(S_t) - I_2 < R_1(S_t)$ or $\hat{F}_1(S_t) + \hat{F}_2(S_t) - I_1 < R_2(S_t)$. (13a)

This could occur when technologies are substitutes, or when maintenance and redeployment costs are excessive. A type II error occurs when:

$$R_k(S_t) < I_k \text{ for } k=1,2$$

$$\text{and} \quad \hat{F}_1(S_t) + \hat{F}_2(S_t) > I_1 + I_2. \tag{13b}$$

Here, technologies may be synergistic and/or maintenance and redeployment costs may be lower than their initial technology acquisition costs.

**Limited foresight.** Now consider the firm suffering from spatial myopia that is somewhat less temporally myopic, i.e., it looks forward a single period. We assume, as before, that technology 1 performs best in state 1, and technology 2 performs best in state 2. If all technology purchase decisions are made only at $t$=0 and the initial state is 1, the firm's decision regarding technology 1 considers whether the following condition holds:

$$R_1(S_0=1)-I_1+\{Pr(S_1=1 \mid S_0=1)R_1(S_1=1)+Pr(S_1=2 \mid S_0=1)max[R_1(S_1=2),-m_1]\}/(1+r)$$
$$> 0. \tag{14}$$

In state 1, it is possible that the expected cash flow from purchasing technology 2 is positive. If $R_2(S_0=1)>-m_2$, the firm considers whether:

$$R_2(S_0=1)-I_2+\{Pr(S_1=1 \mid S_0=1)R_2(S_1=1)+Pr(S_1=2 \mid S_0=1)R_2(S_1=2)\}/(1+r) > 0. \tag{15a}$$

If this condition holds, technology 2 will be deployed at $t=0$. Alternatively, if $R_2(S_0=1)<-m_2$, the firm considers whether:

$$-m_2-I_2+\{Pr(S_1=1 \mid S_0=1)(-m_2)+Pr(S_1=2 \mid S_0=1)[R_2(S_1=2)-c_2]\}/(1+r) > 0. \tag{15b}$$

If this condition holds, technology 2 will be purchased but remain idle in $t=0$. If neither (15a) nor (15b) apply, the firm will avoid technology 2.

Comparing the decision rules under single-period foresight with those used when the firm focuses exclusively on the current period, several new considerations stand out. Performance in the alternative state now receives consideration in the decision regarding each technology. Maintenance costs also factor into the decision criteria. The technology redeployment cost enters into decisions regarding technologies that remain idle in the current period. This can be seen in (15b) and only applies when all technology purchase decisions must be made in the initial period. These considerations offers improvements relative to the earlier criterion under the more extreme form of temporal myopia, $R^k(S_t) > I_k$.

We should also contrast these decision rules with those used in the absence of temporal and spatial myopia. This ideal involves nonmyopic foresight and recognition that when both technologies are deployed simultaneously the resulting revenues associated with technology $k$ are $\hat{R}_k(S_t)$. As such, technologies are purchased and deployed to realize:

$$\max\left(\hat{F}_1(S_t)+\hat{F}_2(S_t)-I_1-I_2, F_1(S_t)-I_1, F_2(S_t)-I_2, 0\right). \tag{16}$$

Decisions guided by (14), (15a), and (15b) deviate from this optimal decision rule. Both Type I and Type II technology investment errors are possible due to the combined effects of temporal and spatial myopia. In moving from focusing on the current period to limited foresight, errors due to neglect of maintenance and redeployment costs are less likely, but still possible. The potential for errors due to synergistic and nonsynergistic technologies persists.

**Summary**

This section examined spatial myopia under alternative assumptions about temporal myopia. Although Levinthal and March (1993) identified these two kinds of myopia, no previous research has explored rigorously their implications for technology investment and deployment decisions. Here is a summary of our key findings.

With nonmyopic foresight, Type I errors can only occur if both technologies are acquired and they are nonsynergistic. Nonmyopic foresight eliminates any other possibilities for Type I errors. Failure to recognize synergies can give rise to Type II errors. When deploying a single technology or no technology, Type II errors are possible.

Combining temporal and spatial myopia brings together several causes of potential errors. The key determinants of error patterns are whether technologies are synergistic or nonsynergistic, and the magnitude of maintenance and redeployment costs relative to the initial investment. Moving from focusing on the current period to limited foresight introduces considerations of performance in the alternative state, maintenance costs, and redeployment costs.

It is important to note that correcting just one of the two forms of myopia may not reduce the probability of errors. Because the two types of myopia may have opposite effects on the perceived values of technologies, eliminating just one type of myopia could increase the probability of errors. Only by alleviating spatial and temporal myopia simultaneously can we be assured that the likelihood of errors is reduced.

## DISCUSSION

Our analysis elaborates and supports Levinthal and March's contention that: "Determining the variety and depth of knowledge to be added to the [knowledge] inventory is filled with potential pitfalls" (1993: 103). Our analysis indicates that even the simplest knowledge inventory problems are indeed quite complex.

By following up on the problem posed by Levinthal and March (1993), our approach follows the knowledge-based view of the firm as elaborated by Conner (1991), Grant (1996), Kogut and Zander (1992), Winter (1987), and others. This view focuses on differentiated knowledge inventories as the basis for competitive advantage. This perspective is not without its shortcomings. Foss (1996) indicates that the existence of unique knowledge is a necessary, but not sufficient condition for the existence of firms. He argues that the knowledge-based view requires a complementary emphasis on contract theory—with its assumption of opportunism—in order to explain the existence and boundaries of firms. It follows that the revenue streams associated with specific knowledge, $R_k(S_t)$, should encompass all revenues and costs—including governance costs—associated with adopting technology $k$. Hence, adoption of a technology implies unique rent-generating potential and efficient governance. Were that not the case, other firms could compete away any rents associated with adopting the technology.

The key insight motivating this study is that real option theory informs the management of knowledge inventories. Kulatilaka's contributions (Kulatilaka & Marcus, 1988; Kulatilaka & Trigeorgis, 1994; Kulatilaka, 1995) are particularly relevant. Recasting the challenge of managing knowledge inventories in option theoretic terms proved insightful. However, this study did not simply borrow from real option theory. Developing the observations of Levinthal and March (1993), we were able to model the implications of temporal and spatial myopia for real option decision making. This is a novel contribution, and one that could be extended to analyze other real option investment behaviors.

Very few studies have acknowledged the behavioral aspects of real option investment decisions.[8] We know of only three articles on real options that have raised the issue of temporal myopia—Chi and Fan (1997), Kogut and Kulatilaka (1994), and Lander and Pinches (1998)—and none provides a comparable detailed analysis of the implications of myopia for real option investment decisions. McDonald (2000) recently argued that managers "rules of thumb" approximate normative option pricing rules for timing investments. His optimistic conclusion was based on managers applying an arbitrary NPV threshold rule, but his analysis did not consider myopia. Our analysis of temporal and spatial myopia raises serious questions about whether simple heuristics can approximate optimal option investment behaviors. Compared with normative option pricing models, behavioral approaches may provide fuller explanations and better predict how managers actually respond when faced with real option acquisition and exercise decisions.

Our analysis motivates some specific propositions regarding the management of knowledge inventories. Consider some implications from our analysis of temporal myopia. We showed that the more limited the temporal horizon of the firm, the more restricted is its knowledge inventory. In the extreme case of uncertainty about the current state, we should observe technology specialists, an expectation consistent with Heiner's (1983) contention about predictable behavior under uncertainty.[9]

It is widely recognized that a short-term focus on current performance is likely to result in underinvestment relative to foresightful decision making (see, e.g., Laverty, 1996). However, in criticizing management for thinking short-term, we neglect the positive aspect that Type I errors become very unlikely. The need to recover initial investments in technology acquisition and deployment from short-term cash flows sets high hurdles for technology adoption. Our analysis pointed out that temporal myopia is most likely to give rise to Type II errors when initial technology acquisition costs are high relative to subsequent switching and maintenance costs. On the other hand, temporal myopia can lead to overinvestment (Type I error) if current acquisition costs are low relative to future switching and maintenance costs.

Unlike previous treatments of path dependency, which emphasize the unique cumulative effects of organizational learning and unique environmental circumstances (see, e.g., Arthur, 1994; Dierickx & Cool, 1989), we demonstrated how path dependency can result from temporal myopia. This occurs because managers who are focused on the short term fail to appreciate the full value-added associated with technological flexibility over longer time horizons. This perspective emphasizes the implications of bounded rationality rather than the behaviors of competitors in determining technology lock-in. These explanations are not mutually exclusive, but strategic management discussions often place greater emphasis on the competitive environment of "technology races" than on the cognitive explanations for competency traps (March, 1991) or core rigidities (Leonard-Barton, 1992). Even in the absence of external constraints on the availability of alternative technologies, firms can lock into a small set of technologies because of the limitations of managers' thinking.

The key characteristic of the external environment that determines technology acquisitions is the extent to which the environmental state is continuous or fluctuates. If a particular environmental state is likely to persist, e.g., $Pr(S_{t+1}=1 \mid S_t=1) > Pr(S_{t+1}=2 \mid S_t=1)$ and $Pr(S_{t+1}=1 \mid S_t=2) > Pr(S_{t+1}=2 \mid S_t=2)$, then forward-looking firms are less likely to invest in alternative technologies. Hence, the earlier contention that the breadth of a firm's knowledge inventory increases with its foresightfulness is moderated by environmental volatility. The relation should be strongest in environments that shift frequently. Furthermore, the higher the technology maintenance costs, the narrower the breadth of the knowledge inventory, for given levels of foresight and environmental volatility.

Moving from a focus on the current period to single-period foresight, the behavioral decision rules regarding technology acquisition and switching became much more complex. The complexity would increase to a much greater extent if we explicitly modeled the decision rules for longer-term foresightfulness. We argued earlier that the complexity of the decision rules under limited foresight presents a prima facie case that managers' decision heuristics focus on the current period or consider only a very limited time horizon when making technology acquisition and deployment decisions. Managers are likely to neglect or strongly discount temporally-distant possibilities. Their technology acquisition and deployment decisions are likely to exhibit behaviors that diverge—possibly in drastic ways—from the normative decision rules derived from optimizing behavior using dynamic programming. This divergence increases with the level of switching costs and the difference in maintenance costs among alternative technologies, rather than the absolute magnitude of the maintenance costs. As would be expected, this divergence also decreases with the discount rate. Firms with high switching costs, wide disparities in maintenance costs for idle technologies, and low discount rates are most likely to benefit from extending the time horizon considered in managing their knowledge inventories.

The section on spatial myopia elaborated the conditions for errors in knowledge inventory management due to neglecting interactions with other technologies. Even in the extreme case of focusing on an individual technologies to the exclusion of all others, there is still option value. This option value arises from the flexibility to deploy or idle the single technology in any given period. Yet spatial myopia may distort perceptions of the added value associated with a technology acquisition relative to considering its deployment in the context of other technologies in the firm's knowledge inventory. Substituting technologies give rise to Type I errors. For complementary technologies, spatial myopia can result in Type II errors. The larger the substituting or complementary effects, the more likely are errors in knowledge inventory management.

When temporal and spatial myopia occur together, the possibilities for errors increase. Technology maintenance and redeployment costs are key determinants of whether temporal myopia contributes to Type I or Type II errors. The higher the maintenance and redeployment costs relative to initial investment costs, the higher the probability of Type I errors relative to Type II errors. Correcting cognitive biases requires simultaneous lengthening of the time horizon and considering technology interactions. Correcting only one kind of myopia can still result in systematic errors. The effects on technology values associated with correcting temporal and spatial myopia may be in the same direction or in opposite directions. If the effects are in the same direction, correcting one form of myopia can reduce the likelihood of errors. However, if the errors are in opposite directions, correcting just one form of myopia could actually increase the probability of errors.

We could extend the analysis of spatial myopia to consider more than two technologies and states. This would allow us to develop a model in which managers consider a limited set of technology interactions rather than focusing on each technology exclusively. For example, if a third technology were introduced, we could assume managers are aware of one or more two-way interactions among pairs of technologies. The lack of awareness of some two-way interactions and the three-way interaction is an alternative way to operationalize spatial myopia. Such an approach would add considerable complexity to the models presented here, particularly if alternative forms of temporal myopia were also considered. This is a possible direction for extending this study.

Cohen and Levinthal's (1990) concept of "absorptive capacity" suggests another direction for extending this study. The models presented here assumed the prices for acquiring technologies were outside managers' control. Alternatively, we could allow for the possibility of investments in absorptive capacity—current investments that reduce subsequent technology adoption costs. A further variation would allow current investments to reduce future maintenance and switching costs. Each of these investments enhance future flexibility, and as such could be modeled as real option investment decisions, with implications for knowledge inventory management.

Alternatively, firms may manage the problem of knowledge inventories by outsourcing some technologies. The present analysis could be extended to specify the conditions under which technology outsourcing dominates technology acquisition for a subset of available technologies. This presents an intermediate alternative between the extremes of acquiring and not acquiring technologies. Under uncertainty, investments reducing technology access and switching costs among partners have option value. Extending the present paper to outsourcing requires specifying the motivations for both the technology accessing firm and technology supplying firm to enter into partnership.

# ENDNOTES

[1] If we allow the firm to temporarily idle and then redeploy a technology, even purchasing a single technology becomes an option pricing problem. For the time being, we suppress this possibility by assuming the firm will always have a technology in use if it decides to buy one or both technologies.

[2] Finance approaches to real option pricing rely on the assumption that the underlying asset associated with the option is traded. This allows the use of available market data to convert the probabilities of future states to their risk-neutral values (Cox, Ingersoll, & Ross, 1985; Cox, Ross, & Rubinstein, 1979; Trigeorgis & Mason, 1987). The risk-free interest rate can then be used as the discount rate, *r*. The finance approach is not viable for strategic investments involving nontraded firm-specific idiosyncratic assets with cash flows that cannot be matched to a traded asset (or combination of traded assets). This shortcoming in existing real option pricing techniques leaves managers without specific guidance regarding the choice of discount rate to apply in many real option valuation problems. As such, it is reasonable to assume that firms adopt a discount rate that is somewhat arbitrary and bounded by the risk-free rate and the firm's cost of capital.

[3] We assume the technology maintenance cost is less than its disposal cost. If not, the firm would simply dispose of technology 1 when state 2 occurs.

[4] This decision criterion assumes $R_1(S_1=2) > -m_1$.

[5] Explicit consideration of the switching cost, $c_{21}$, reduces the probability of Type 1 errors relative to using decision criterion (7), which gives no consideration to $c_{21}$. With two-period foresight, $c_{21}$ would always receive consideration when technology 2 is purchased after technology 1.

[6] Thus, we must be able to write a comparable decision rule for the firm when operating with technology 2 at time t-1:

$$R_1(S_t=1)-c_{21}-m_2+\{Pr(S_{t+1}=1\,|S_t=1)[R_1(S_{t+1}=1)-m_2]+Pr(S_{t+1}=2\,|S_t=1)[R_2(S_{t+1}=2)-c_{12}-m_1]\}/(1+r)$$

$$> R_2(S_t=1)-m_1+\{Pr(S_{t+1}=1 \mid S_t=1)R_2(S_{t+1}=1)+Pr(S_{t+1}=2 \mid S_t=1)R_2(S_{t+1}=2)-m_1\}/(1+r).$$

The expression comparable to (10) is:

$$[R_1(S_t=1)-R_2(S_t=1)-c_{21}-(m_2-m_1)]+Pr(S_{t+1}=1 \mid S_t=1)[R_1(S_{t+1}=1)-R_2(S_{t+1}=1)-(m_2-m_1)]/(1+r)$$

$$> Pr(S_{t+1}=2 \mid S_t=1)c_{12}/(1+r).$$

[7] Using (10) and the comparable inequality in the previous endnote, it is also possible to solve for the switching cost values, $c_{12}$* and $c_{21}$*, that cause the firm to be indifferent between switching and not switching. Switching costs in excess of $c_{12}$* and $c_{21}$* would lead the firm to operate with the same technology in all periods.

[8] Shefrin and Statman (1993) drew from behavioral decision theory to argue that some investors prefer one financial option over another because of the ways identical cash flows are framed. Steil (1993) appealed to cognitive biases to explain the use of hedging instruments by corporate treasurers to manage foreign exchange risk. Howell and Jägle (1997) collected laboratory and questionnaire data to examine managers' subjective valuations of growth options. They found only weak correspondence between managers' perceptions and option theory. Busby and Pitts (1997) reported very few decision-makers seemed to be aware of real option research but, mostly, their intuitions agreed with the qualitative prescriptions from such work.

[9] Heiner's approach has been criticized (see Bookstaber & Langsam, 1985; Garrison, 1985; Driver, 1992; cf. Heiner, 1985), but these critiques of technical aspects of his article do not undermine the relevance of his core argument in the context of our models of knowledge investments under myopia.

## REFERENCES


Arthur, W. B. 1994. Increasing returns and path dependence in the economy. Ann Arbor, Michigan: University of Michigan Press.

Barney, J. B. 1986. Strategic factor markets: Expectations, luck, and business strategy. Management Science, 32: 1231-1241.

Barney, J. B. 1991. Firm resources and sustained competitive advantage. Journal of Management, 17: 99-120.

Bercovitz, J. E. L., de Figueiredo, J. M., & Teece, D. J. 1997. Firm capabilities and managerial decision making: A theory of innovation biases. In R. Garud, Nayyar, P. R., & Shapira, Z. B. (eds.). Technological innovation: Oversights and foresights: 233-259. New York: Cambridge University Press.

Bookstaber, R. & Langsam, J. 1985. Predictable behavior: Comment. The American Economic Review, 75: 571-575.

Busby, J. S. & Pitts, C. G. C. 1997. Real options in practice: An exploratory survey of how finance officers deal with flexibility in capital appraisal. Management Accounting Research, 8:169-186.

Chi, T. & Fan, D. 1997. Cognitive limitations and investment “myopia”. Decision Sciences, 28: 27-57.

Cohen, W. M. & Levinthal, D. A. 1990. Absorptive capacity: A new perspective on learning and innovation. Administrative Science Quarterly, 35: 128-152.

Cohen, M. D., March, J. G. & Olsen, J. P. 1972. A garbage can model of organizational choice. Administrative Science Quarterly, 17:1-25.

Conner, K. R. 1991. A historical comparison of resource-based theory and five schools of thought within industrial organization economics: Do we have a new theory of the firm? Journal of Management, 17: 121-154.

Cox, J., Ingersoll, J., & Ross, S. 1985. An intertemporal general equilibrium model of asset prices. Econometrica, 53: 363-384.

Cox, J. C., Ross, S. A., Rubinstein, M. 1979. Option pricing: A simplified approach. Journal of Financial Economics, 7: 229-263.

Cyert, R. M. & March, J. G. 1963. A behavioral theory of the firm. Englewood Cliffs, New Jersey: Prentice-Hall.

Dierickx, I. & Cool, K. 1989. Asset stock accumulation and sustainability of competitive advantage. Management Science, 35: 1504-1511.

Dixit, A. K. & Pindyck, R. S. 1994. Investment under uncertainty. Princeton, New Jersey: Princeton University Press.

Driver, C. F. 1992. The origin of predictable behavior: Comment. The American Economic Review, 82: 368.

Foss, N. J. 1996. Knowledge-based approaches to the theory of the firm: Some critical comments. Organization Science, 7: 470-476.

Garrison, R. W. 1985. Predictable behavior: Comment. The American Economic Review, 75: 576-578.

Garud, R. & Nayyar, P. R. 1994. Transformative capacity: Continual structuring by intertemporal technology transfer. Strategic Management Journal, 15: 365-385.

Grant, Robert M. 1996. Toward a Knowledge-Based Theory of the Firm. Strategic Management Journal, 17: 109-122.

Heiner, R. A. 1983. The origin of predictable behavior. The American Economic Review, 73: 560-595.

Heiner, R. A. 1985. Predictable behavior: Reply. The American Economic Review, 75: 579-585.

Howell, S. D. & Jägle, A. J. 1997. Laboratory evidence on how managers intuitively value real growth options. Journal of Business Finance and Accounting, 24: 915-935.

Hurry, D. 1994. Shadow options and global exploration strategies. In Shrivastava, P., Huff, A. S., & Dutton, J. E. (Eds.), Advances in strategic management, 10A: 229-248. Greenwich, Connecticut: JAI Press.

Kahneman, D. & Lovallo, D. 1993. Timid choices and bold forecasts: A cognitive perspective on risk taking. Management Science, 39: 17-31.

Kogut, B. & Kulatilaka, N. 1994. Options thinking and platform investments: Investing in opportunity. California Management Review, 36(2): 52-71.

Kogut, B. & Zander, U. 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. Organization Science, 3: 383-397.

Kulatilaka, N. & Marcus, A. J. 1988. General formulation of corporate real options. In A. Chen (Ed.), Research in finance, Vol. 7: 183-199. Greenwich, Connecticut: JAI Press.

Kulatilaka, N. & Trigeorgis, L. 1994. The general flexibility to switch: Real options revisited. International Journal of Finance, 6: 778-798.

Kulatilaka, N. 1995. The value of flexibility: A general model of real options. In L. Trigeorgis (Ed.), Real options in capital investment: Models, strategies, and applications: 89-107. Westport, Connecticut: Praeger.

Lander, D. M. & Pinches, G. E. 1998. Challenges to the practical implementation of modeling and valuing real options. The Quarterly Review of Economics and Finance, 38 (Special Issue): 537-567.

Laverty, K. J. 1996. Economic "short-termism": The debate, the unresolved issues, and the implications for management practice and research. Academy of Management Review, 21: 825-860.

Leonard-Barton, D. 1992. Core capabilities and core rigidities: A paradox in managing new product development. Strategic Management Journal, 13 (Summer Special Issue): 111-125.

Levinthal, D. & March, J. G. 1993. The myopia of learning. Strategic Management Journal, 14(S2): 95-112.

Levitt, B. & March, J. G. 1988. Organizational learning. Annual Review of Sociology, 14: 319-340.

March, J. G. 1991. Exploration and exploitation in organizational learning. Organization Science, 2: 71-87.

March, J. G. 1994. A primer on decision making: How decisions happen. New York: Free Press.

March, J. G. & Simon, H. A. 1958. Organizations. New York: John Wiley.

McDonald, R. L. 2000. Real options and rules of thumb in capital budgeting. In Brennan, M. J. & Trigeorgis, L. (Eds.), Project flexibility, agency, and competition: New developments in the theory and application of real options. New York: Oxford University Press.

McDonald, R. L. & Siegel, D. R. 1985. Investment and the valuation of firms when there is an option to shut down. International Economic Review, 26: 331-349.

Ocasio, W. 1997. Towards an attention-based view of the firm. Strategic Management Journal, 18 (Summer Special Issue): 187-206.

Shapira, Z. 1995. Risk taking: A managerial perspective. New York: Russell Sage Foundation.

Shefrin, H. & Statman, M. 1993. Behavioral aspects of the design and marketing of financial products. Financial Management, 22(2): 123-134.

Steil, B. 1993. Corporate foreign exchange risk management: A study in decision making under uncertainty. Journal of Behavioral Decision Making, 6: 1-31.

Teece, D. J., Pisano, G., & Shuen, A. 1997. Dynamic capabilities and strategic management. Strategic Management Journal, 18: 509-533.

Trigeorgis, L. & Mason, S. P. 1987. Valuing managerial flexibility. Midland Corporate Finance Journal, 5(1): 14-21.

Winter, S. G. 1987. Knowledge and competence as strategic assets. In Teece, D. (Ed.), The competitive challenge. Cambridge, Massachusetts: Ballinger.

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