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KNOWLEDGE INVENTORIES AND MANAGERIAL MYOPIA

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Managing knowledge inventories is the central issue posed by the knowledge-based view of the firm. Knowledge inventory management involves acquiring, retaining, deploying, idling, and abandoning technologies. Because of future opportunities to switch technologies over time, managing knowledge inventories requires valuing flexibility. Real option theory presents normative conceptual frameworks and 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 reveals possible sources and patterns of technology management decision errors. This study highlights the cognitive sources of path dependencies and organizational rigidities.

The starting point for this research is the challenge of 'maintaining appropriate knowledge inventories' recognized by Levinthal and March (1993: 103). 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).

Levinthal and March (1993) linked the challenges of knowledge management to bounded rationality. They highlighted two shortcomings of managers' cognitive abilities relative to the demands of knowledge inventory management. *Temporal myopia* involves focusing on the short-term. *Spatial myopia* is the lack of awareness of other technologies available within or outside the organization. Elaborating the nature of these cognitive limitations is fundamental to understanding knowledge management and knowledge-based competitive advantages.[1]

Key words: myopia; technology management; knowledge-based view; real options; flexibility
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[1] The knowledge-based view of the firm focuses on differentiated knowledge inventories as the basis for competitive advantages. Contributors to this view include Conner (1991), Grant (1996), Kogut and Zander (1992), Leonard-Barton (1992), Liebeskind (1996), Spender (1996), and Winter (1987). Leonard-Barton (1992) identified four dimensions of knowledge: (1) employee knowledge and skills, (2) technical systems, (3) managerial systems, and (4) values and norms. Her broad conceptualization of the knowledge set of the firm includes everything that resource-based theorists would consider except physical resources. As such, the knowledge-based view overlaps broadly with the

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Knowledge inventory management involves acquiring, retaining, deploying, idling, and abandoning technologies over time. Managers approach these decisions uncertain about which technologies may be most appropriate for current and future use. Firms may add technologies to their knowledge inventories without deploying them immediately. They may idle previously used technologies, yet continue to make the investments necessary to maintain them for reactivation in the future. The willingness of firms to invest in idle technologies reflects their interest in maintaining flexibility to switch technologies in the future. Large knowledge inventories provide broad repertoires of organizational responses to future contingencies.

Independent of management 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) addressed state-contingent switching among alternative technologies. Their articles portrayed investments in alternative technologies as real option purchases and subsequent changes in the technology-in-use as option exercise decisions. Their approach to valuing such options requires forward-looking consideration of switching costs and the performances of alternative technologies under possible future states. Although the real option approach is a helpful way to frame the problem of managing knowledge inventories, the decision rules offered in that research make unrealistic assumptions about managers' foresight (Chi and Fan, 1997). Real options research emphasizes normative decision rules that assume away many practical problems and managers' own limitations (Lander and Pinches, 1998).

This paper draws from real option research to frame the knowledge inventory problem. However, departing from previous real option research, we explore the implications of managerial myopia for knowledge inventory management. The first section describes the knowledge inventory problem and 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. Our analyses point out the cognitive sources of organizational rigidities, path dependencies, and knowledge-based competitive advantages. 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 making decisions under uncertainty about a firm's portfolio of technologies. If technology investments require sunk costs and extended time horizons, these decisions become complex. Managers cannot costlessly reverse current decisions if the state of the world changes. They face disposal or ongoing 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 become inaccessible if not acquired during the window of opportunity. Such situations characterize 'technology races' (Conner, 1988; Lerner, 1997) 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 firm must decide the composition of their knowledge inventory given two available technologies. These alternatives involve different inputs and/or outputs. For example, Tegarden, Hatfield, and Echols (1999) portrayed personal computer manufacturers' primary technology choice as the selection of Apple- or IBM-compatible microprocessor technologies. Because of the unique design and manufacturing challenges posed by these two distinct technologies, firms have tended to specialize in just one. Nevertheless, a minority of firms have switched technologies, almost always moving toward IBM-compatible technology as it emerged as the dominant design in the early 1980s.

To keep the problem simple, initially we assume the technologies are substitutes. The performance characteristics of the two technologies are such that a firm would not implement them together. There

resource-based (e.g., Barney, 1991) and dynamic capabilities (Teece, Pisano, and Shuen, 1997) views.

are many examples of such choices. Under uncertainty, a firm may retain access to two alternative energy sources (e.g., gas and coal), two alternative designs (e.g., electronic and mechanical), or two alternative suppliers (e.g., domestic and foreign). They do so even though only one is used at any point in time. On the output side, the technology alternatives involve knowledge of different customer groups, products, and geographic markets. The organization may be active in only one market, yet continue to invest in distributor and customer relations in another market. Such investments allow firms to switch between two alternative distribution channels or customer groups.

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 probabilities 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 suffice. However, possessing an alternative technology may add value under state uncertainty. This value can be expressed in terms of the value of the option to switch technologies. The option to switch involves both a put—the option to idle one technology—and a call—the option to deploy another technology—at costs that are more favorable than if no previous investments had been made in these 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, $k \in (1, 2)$, depends 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.[2] Furthermore, let c_{12} indicate the cost of switching from technology 1 to 2. The firm avoids such costs if it 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. The models in each of these articles assume the firm already possessed both technologies and do not examine the initial technology acquisition decision. Here we consider both 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.[3] 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, we can use standard NPV analyses with risk-adjusted discount rates to derive V_1 and V_2. By contrast, 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 using the optimal investment strategy is $\max[V_1 - I_1, V_2 - I_2, V_{12} - I_1 - I_2, 0]$.

[2] Foss (1996) clarified the knowledge-based view by noting that unique knowledge is a necessary, but not sufficient condition for the existence of firms. He argued 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 revenues, $R_k(S_t)$, should encompass all revenues and costs—including governance costs—associated with adopting technology k.

[3] 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 have a technology in use in each period if it decides to buy one or both technologies.

To solve for the value of holding both technologies, V_{12}, management must specify their intended technology deployment strategy. Optimal behavior requires choosing a current technology to maximize the present value of discounted expected future revenues net of switching costs and maintenance costs over the entire period of operation.[4] Let $F(S_t)$ 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.[5] For a firm holding both technologies, its initial technology choice is found by solving:

$$F(S_0) = \max\{R_1(S_0) - m_2 + E_0[F_1(S_1)]/(1+r),\ R_2(S_0) - m_1 + E_0[F_2(S_1)]/(1+r)\} \tag{1a}$$

where m_k is the positive maintenance cost that must be incurred each period in order to retain the inactive technology k and $E_0[F_1(S_1)]$ and $E_0[F_2(S_1)]$ are the expectations at period 0 of firm value in period 1 when operating in period 0 with technologies 1 and 2, respectively. If the firm arrives at time t operating with technology *1* in state S_t, its technology choice is the solution to:

$$F(S_t) = \max\{R_1(S_t) - m_2 + E_t[F_1(S_{t+1})]/(1+r),\ R_2(S_t) - c_{12} - m_1 + E_t[F_2(S_{t+1})]/(1+r)\} \tag{1b}$$

This model presents several implications for optimal management of knowledge inventories. 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 and maintenance costs, the lower the value associated with holding an alternative technology. Third, if switching costs are negligible ($c_{12} = c_{21} = 0$) and maintenance costs for the two technologies are equivalent ($m_1 = m_2$), optimizing Equation (1b) is straightforward. The firm simply chooses the technology maximizing current period cash flows and does not need to consider the future. However, with switching costs or differential maintenance costs, looking forward all the way to the final period T is the only way to derive the optimal pattern of technology deployment decisions.

Our interest here is not in the well-documented details of the dynamic programming approach to derive the optimal solution to the specified problems.[6] Rather, we 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 shortsighted. Furthermore, the optimizing 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 spatially myopic 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 spatial myopia problem of considering technology acquisition and deployment decisions in isolation. Then we analyze the two forms of myopia together.

[4] Levitt and March (1988) and Garud and Nayyar (1994) alert us to the possibility that inactive technologies require ongoing investments for their maintenance. Knowledge 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.

[5] 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, and Ross, 1985; Cox, Ross, and Rubinstein, 1979; Trigeorgis and 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 combinations of traded assets). This shortcoming in existing real option pricing techniques leaves managers without specific guidance regarding the discount rates 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 risk-adjusted cost of capital.

[6] For these details see Kulatilaka (1995) and Dixit and Pindyck (1994: ch. 4).

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 five causes for 'economic short-termism.' Two of these causes—flawed management practice (such as capital budgeting criteria favoring short-term performance) and managerial opportunism—reflect shortcomings of management. 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 and Simon, 1958) and results in sequential attention to goals (Cyert and March, 1963; Cohen, March, and Olsen, 1972). Cognitive limits force managers to allocate attention between current and future considerations (Levinthal and March, 1993). Pressing current organizational problems are the most salient motivators of organizational search, not future-oriented considerations. Following in the tradition of Cyert, March, and Simon (March and Simon, 1958; Cyert and 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 or 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. In this case, managers must choose between alternative production methods or markets, yet they find themselves without sufficient information to assess the present status of critical decision contingencies. For example, managers may lack information about the availability, quality, and price of inputs when choosing between production technologies. They may be uncertain about customer preferences and competition when choosing which market to serve. Such uncertainties often characterize emerging industries, but may also hold for mature industries undergoing changes.

We assume that 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 $Pr(S_t = 1|S_{t-1}) = Pr(S_t = 1)$ and $Pr(S_t = 2|S_{t-1}) = Pr(S_t = 2)$. 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 pay-off. They choose technology 1 if:

$$\begin{aligned} Pr(S_t = 1)R_1(S_t = 1) + Pr(S_t = 2)R_1(S_t = 2) \\ - I_1 > Pr(S_t = 1)R_2(S_t = 1) \\ + Pr(S_t = 2)R_2(S_t = 2) - I_2 \end{aligned} \tag{2}$$

and the expected pay-off 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 expected current 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 (2) 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 full time horizon (through 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. 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 pay-off 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.[7] 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 and switching costs.

[7] 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.

Because of maintenance and switching 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:

$$R_2(S_t = 2) - R_1(S_t = 2) > c_{12} + (m_1 - m_2) \tag{3a}$$

and

$$R_1(S_t = 1) - R_2(S_t = 1) > c_{21} + (m_2 - m_1) \tag{3b}$$

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 (3a) and (3b) are reversed, the firm will lock into a single technology for its duration.

Up to this point, we have assumed that disposal costs exceed maintenance costs, so the firm retains previously acquired technologies. Temporal myopia results in a technology *retention error* if future maintenance costs exceed the cost of abandoning the idle technology and later acquiring it anew when the state changes. However, if the current maintenance cost associated with an idle technology exceeds its disposal cost, temporally myopic managers will readily abandon the idle technology. *Abandonment errors* occur when firms fail to consider future state changes that would make redeploying the idle technology desirable and the increment to revenues that redeployment could provide. Quick abandonment also overlooks the future cost of reacquiring the technology, which may be considerably more than maintaining a technology already held by the firm. The perception that a particular technology is the 'industry standard' may lead managers to abandon alternative technologies. As such, industry technology norms promote short-run adaptation over long-run adaptability (March, 1991).

When the firm only considers the current period 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.

These observations point out the irony that a firm that knows the current state is not necessarily better off than a firm that does not know the current state. Suppose the firm that does not know the current state chooses to deploy technology 1 in all periods. By contrast, the firm that can discern the current state chooses the more complex strategy of adopting technology 1 in state 1 and technology 2 in state 2. Although this strategy matches the appropriate technology to the state of the world, it overlooks the effects of maintenance and switching costs over time. Subsequent maintenance costs may cause the firm that knows the current state to underperform the firm that does not. In essence, the firm that knows the current state may overinvest in response to low-probability states.

Limited foresight

Also of interest is the situation in which managers are able to discern the current state prior to making 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:

$$R_1(S_0 = 1) - I_1 + [Pr(S_1 = 1|S_0 = 1)R_1(S_1 = 1) + Pr(S_1 = 2|S_0 = 1)R_1(S_1 = 2)]/(1 + r) > 0 \quad (4)$$

and exceeds that of technology 2.[8] That is,

$$\begin{aligned} &R_1(S_0 = 1) - I_1 + [Pr(S_1 = 1|S_0 = 1)R_1(S_1 = 1) \\ &\quad + Pr(S_1 = 2|S_0 = 1)R_1(S_1 = 2)]/(1 + r) \\ &\quad > R_2(S_0 = 1) - I_2 + [Pr(S_1 = 1|S_0 = 1)R_2(S_1 \\ &\quad = 1) + Pr(S_1 = 2|S_0 = 1)R_2(S_1 = 2)]/(1 + r) \end{aligned}$$

or, rearranging terms,

$$\begin{aligned} &R_1(S_0 = 1) - R_2(S_0 = 1) + \{Pr(S_1 = 1|S_0 \\ &\quad = 1)[R_1(S_1 = 1) - R_2(S_1 = 1)] \\ &\quad + Pr(S_1 = 2|S_0 = 1)[R_1(S_1 = 2) \\ &\quad - R_2(S_1 = 2)]\}/(1 + r) > I_1 - I_2 \end{aligned} \quad (5)$$

This inequality summarizes the decision heuristic used by managers with single-period foresight. 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 (4) and (5).

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

$$\begin{aligned} &Pr(S_1 = 2|S_0 = 1)[R_2(S_1 = 2) - R_1(S_1 = 2) \\ &\quad - c_{12} - m_1]/(1 + r) > I_2 + [1 \\ &\quad + Pr(S_1 = 1|S_0 = 1)/(1 + r)]m_2 \end{aligned} \quad (6)$$

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

Comparing (4) and (6), 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 for 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:

$$\begin{aligned} &R_2(S_t = 2) - I_2 - c_{12} - m_1 + \{Pr(S_{t+1} = 2|S_t \\ &\quad = 2)[R_2(S_{t+1} = 2) - m_1] - Pr(S_{t+1} = 1|S_t \\ &\quad = 2)(m_2 + c_{21})\}/(1+r) > R_1(S_t = 2) \\ &\quad + \{Pr(S_{t+1} = 2|S_t = 2)R_1(S_{t+1} = 2) \\ &\quad + Pr(S_{t+1} = 1|S_t = 2)R_1(S_{t+1} \\ &\quad = 1)\}/(1+r) \end{aligned} \tag{7}$$

This decision rule assumes the firm will subsequently revert back to using technology 1 when state 1 occurs. Comparing Equations (6) and (7) 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 avoided maintenance costs on the idle technology enhance firm value. Furthermore, explicit consideration of the switching cost, c_{21}, in (7) reduces the probability of Type I errors relative to using decision criterion (6), 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.

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:

$$\begin{aligned} &R_2(S_t = 2) - c_{12} - m_1 + \{Pr(S_{t+1} = 1|S_t \\ &\quad = 2)[R_1(S_{t+1} = 1) - c_{21} - m_2] + Pr(S_{t+1} \\ &\quad = 2|S_t = 2)[R_2(S_{t+1} = 2) - m_1]\}/(1+r) \\ &\quad > R_1(S_t = 2) - m_2 + \{Pr(S_{t+1} = 1|S_t \\ &\quad = 2)R_1(S_{t+1} = 1) + Pr(S_{t+1} = 2|S_t \\ &\quad = 2)R_1(S_{t+1} = 2) - m_2\}/(1+r) \end{aligned} \tag{8}$$

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 (8) as:

$$\begin{aligned} &[R_2(S_t = 2) - R_1(S_t = 2) - c_{12} - (m_1 - m_2)] \\ &\quad + Pr(S_{t+1} = 2|S_t = 2)[R_2(S_{t+1} = 2) \\ &\quad - R_1(S_{t+1} = 2) - (m_1 - m_2)]/(1+r) \\ &\quad > Pr(S_{t+1} = 1|S_t = 2)c_{21}/(1+r) \end{aligned} \tag{9}$$

Decision rule (9) 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.[9] Expression (9) 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.[10] The difference in maintenance costs

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

$$\begin{aligned} &R_1(S_t = 1) - c_{21} - m_2 + \{Pr(S_{t+1} = 1|S_t = 1)[R_1(S_{t+1} = 1) \\ &\quad - m_2] + Pr(S_{t+1} = 2|S_t = 1)[R_2(S_{t+1} = 2) - c_{12} - m_1]\}/ \\ &\quad (1+r) > R_2(S_t = 1) - m_1 + \{Pr(S_{t+1} = 1|S_t = 1)R_2(S_{t+1} \\ &\quad = 1) + Pr(S_{t+1} = 2|S_t = 1)R_2(S_{t+1} = 2) - m_1\}/(1+r) \end{aligned}$$

The expression comparable to (9) is:

$$\begin{aligned} &[R_1(S_t = 1) - R_2(S_t = 1) - c_{21} - (m_2 - m_1)] + Pr(S_{t+1} \\ &\quad = 1|S_t = 1)[R_1(S_{t+1} = 1) - R_2(S_{t+1} = 1) - (m_2 - m_1)]/ \\ &\quad (1+r) > Pr(S_{t+1} = 2|S_t = 1)c_{12}/(1+r) \end{aligned}$$

[10] Using (9) and the comparable inequality in the previous footnote, 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.

$(m_1 - m_2)$, 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) foresight and derived the resulting decision heuristics. Despite these simplifying assumptions, the decision rules regarding acquiring and deploying technologies under single-period foresight are somewhat complex. However, this complexity is modest compared with decision rules under multiperiod foresight. The complexity of decision rules under multiperiod foresight presents a *prima facie* case that managers' knowledge inventory decisions either neglect the future or exhibit very limited foresight. It seems unlikely that boundedly rational managers follow the more sophisticated decision rules arising with multiperiod foresight, 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 current expected value. Type I errors are unlikely. Errors 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 increasingly complex as we expand the time horizon considered by management.

SPATIAL MYOPIA: ALONE AND TOGETHER WITH TEMPORAL MYOPIA

A second form of myopia identified by Levinthal and March (1993) is the tendency to overlook distant places, or 'spatial myopia.' Spatial myopia is the lack of awareness of other technologies within or outside the firm. Managers' cognitive limitations and boundaries within and between organizations cause spatial myopia. Kahneman and Lovallo (1993) portrayed managers as considering investment decisions singularly rather than evaluating them as part of the firm's overall portfolio (see also Bercovitz, de Figueiredo, and Teece, 1997). They labeled the resulting biases 'isolation errors.' In the real options literature, we find a similar contention. Hurry (1994) indicated that organizations may possess unrecognized 'shadow options.'

Spatial myopia has two implications: (1) it limits the set of alternative technologies considered for implementation, and (2) it eliminates consideration of interactions among technologies when deployed at the same time. Although Levinthal and March's (1993) discussion of spatial myopia emphasized the first implication, they did not miss the latter. They described how organizations socially construct definitions of problems that decompose them into simpler problems for assignment to organizational subunits. Decomposition makes problems more tractable but avoids the insights that could come from approaching them holistically.

Here we focus on overlooked interactions among technologies as an expression of spatial myopia, rather than analyzing the neglect of substitute technologies. There are several reasons for this choice. First, errors from overlooking substitute technologies are straightforward. They involve a simple extension of our earlier discussion of technology acquisition under temporal myopia. The previous section elaborated decision rules considering two substitute technologies. If an overlooked third technology offered superior revenues in at least one state or lower switching and maintenance costs, then considering only two alternatives results in a potential error. Otherwise, there is no error. By contrast, interactions among technologies can either enhance or detract from their stand-alone values, resulting in a richer array of possible outcomes and errors. Finally, neglect of substituting technologies has been analyzed elsewhere. Levinthal (1997) modeled the implication that organizations engaging in proximate search get stuck on local peaks in the fitness landscape. Previous research on organizational adaptation has not analyzed the case of neglected interactions among technologies in such depth.

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 with large initial costs. Such path dependencies lock firms into repeated use of an established technology. In such cases, avoidance 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, then we turn to managers' decisions combining both spatial and temporal myopia.

Spatial myopia alone

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 (as in the models presented earlier). Kulatilaka and Trigeorgis (1994) and Kulatilaka (1995) discussed the correspondence between these two types of decisions and their optimal solution approach. As with the option to switch, the flexibility to shut down and restart a project adds option value. Kulatilaka's (1995) approach to valuing such options generalizes earlier work by McDonald and Siegel (1985).

Consider two technologies, $k \in (1, 2)$, that have initial investment costs I_k. These technologies are neither mutually exclusive nor are their pay-offs independent. They 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 pays c_k to redeploy technology k after it has been idle.

Let $G_k(S_t)$ denote the present value at t (using the discount rate, r) of net profit flows from technology k assuming foresightful behavior in each period up to the final period, T. Assume the firm must decide in period 0 whether to buy the two available technologies. With nonmyopic foresight, the value of technology k at the time of initial investment is:

$$G_k(S_0) = \max\{R_k(S_0) + E_0[G_u(S_1)]/(1+r), \\ -m_k + E_0[G_i(S_1)]/(1+r)\} \quad (10a)$$

where $E_0[G_u(S_1)]$ and $E_0[G_i(S_1)]$ are expectations of period 1 present values assuming technology k is either used or idle in period 0. If faced with a now-or-never decision, the firm invests if $G_k(S_0) > I_k$. If the technology is operating, at time t its technology choice problem is similar to (10a). If the technology is idle, upon arriving at time t its value from that point on is:

$$G_k(S_t) = \max\{R_k(S_t) - c_k + E_t[G_u(S_{t+1})]/ \\ (1+r), -m_k + E_t[G_i(S_{t+1})]/(1+r)\} \quad (10b)$$

With nonmyopic foresight, this problem would be solved recursively taking into consideration the full time horizon. Based on independent assessments of each technology, the firm may employ both technologies, just one of the technologies, or neither technology at time t. Operating under spatial myopia, managers perceive the resulting knowledge inventory and pattern of technology deployment as ideal. 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 firm.

Alternatively, simultaneous deployment may harm firm performance relative to expectations. Using more than one technology may produce detrimental competition for internal resources or their products may compete for sales. As such, actual revenues fall short of the spatially myopic expectation, i.e., $\hat{R}_1(S_t) + \hat{R}_2(S_t) < R_1(S_t) + R_2(S_t)$. The returns to one or both technologies are negatively affected by deploying the other technology. This arises when technologies are substitutes rather than complements.

To facilitate discussion of technology deployment errors, we need a nonmyopic benchmark. Let $H(S_t)$ be the value of the firm's knowledge inventory in period t if it purchases both technologies. $H(S_t)$ assumes technology deployment patterns that are optimal taking into consideration interactions and the full time horizon. The initial value of holding both technologies is:

$$H(S_0) = \max\{\hat{R}_1(S_0) + \hat{R}_2(S_0) + E_0[H_{1,2}(S_1)]/(1+r),\ R_1(S_0) - m_2 + E_0[H_1(S_1)]/(1+r),\ -m_1 + R_2(S_0) + E_0[H_2(S_1)]/(1+r),\ -m_1 - m_2 + E_0[H_\phi(S_1)]/(1+r)\} \quad (11)$$

$\hat{R}_1(S_0) + \hat{R}_2(S_0)$ is the revenue realized when both technologies operate together. $R_1(S_0) - m_2$, and $R_2(S_0) - m_1$ are the revenues associated with operating only technology 1 or technology 2, respectively, and $-m_1 - m_2$ is the revenue from idling both technologies. The $E_0[\cdot]$ terms reflect the period 0 expectations of the period 1 firm value given the technology deployment strategy in the initial period.

The nonmyopic firm makes technology investments based on: $\max\{H(S_0) - I_1 - I_2, G_1(S_0) - I_1, G_2(S_0) - I_2, 0\}$. By contrast, the spatially myopic firm only considers whether $G_k(S_0) > I_k$ for each technology. Because the spatially myopic firm considers each technology in isolation, it has a reduced choice set of possible strategies relative to the nonmyopic firm. This can cause several potential errors when deciding on the composition of the firm's knowledge inventory. Here we briefly discuss the potential errors associated with: (1) purchasing both technologies, (2) purchasing just one technology, and (3) purchasing neither technology.

The first outcome, in which $G_k(S_0) > I_k$ holds for both technologies, is not problematic for synergistic technologies. Both technologies would be acquired with or without spatial myopia. However, even if the spatially myopic firm purchases both technologies, it may fail to realize the maximum possible value, $H(S_0)$, because its pattern of technology deployment over time is suboptimal. On the other hand, it may overinvest if the technologies are incompatible. This occurs if $G_1(S_0) > H(S_0) - I_2$ or $G_2(S_0) > H(S_0) - I_1$. If one of these conditions holds, the firm would be better off purchasing a single technology even if it were able to undertake the optimal two-technology deployment strategy. The result is a Type I technology investment error due to spatial myopia.

The intermediate case involves purchasing one technology but not the other. For nonsynergistic technologies, spatially myopic managers still make the best possible choice. However, for synergistic technologies, the spatially myopic decision to purchase only one technology results in a Type II error if $H(S_0) - I_1 - I_2$ exceeds $G_1(S_0) - I_1$ or $G_2(S_0) - I_2$.

The third situation, in which neither technology is purchased, is straightforward. The firm's decision is based on $G_k(S_0) < I_k$ for both technologies. 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. A Type II error occurs when $H(S_0) - I_1 - I_2 > 0$.

This background on spatial myopia sets the stage for considering spatial and temporal myopia together.

Spatial and temporal myopia together

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. This section contrasts the knowledge inventory investments of (1) the firm focused on the current period, (2) the firm with limited (single-period) foresight, and (3) the nonmyopic firm.

Assume managers only consider the current period and also suffer from spatial myopia. Under these conditions, technology investment decisions turn on whether the perceived value of a technology's single-period revenue exceeds its investment cost, i.e., whether $R_k(S_0) > I_k$.

Now consider the firm suffering from spatial myopia that is somewhat less temporally myopic. In this case, managers look 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 occur only at $t = 0$ and the initial state is 1, the firm's decision regarding technology 1 considers whether the following condition holds:

$$R_1(S_0 = 1) - I_1 + \{Pr(S_1 = 1|S_0 = 1)R_1(S_1 = 1) + Pr(S_1 = 2|S_0 = 1)\max[R_1(S_1 = 2), -m_1]\}/(1 + r) > 0 \quad (12)$$

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:

$$R_2(S_0 = 1) - I_2 + \{Pr(S_1 = 1|S_0 = 1)R_2(S_1 = 1) + Pr(S_1 = 2|S_0 = 1)R_2(S_1 = 2)\}/(1 + r) > 0 \quad (13a)$$

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:

$$-m_2 - I_2 + \{Pr(S_1 = 1|S_0 = 1)(-m_2) + Pr(S_1 = 2|S_0 = 1)[R_2(S_1 = 2) - c_2]\}/(1 + r) > 0 \quad (13b)$$

If this condition holds, the firm will purchase technology 2 but keep it idle in $t = 0$. If neither (13a) nor (13b) applies, 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 acquisition 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 (but does not factor into decisions regarding technologies purchased for immediate deployment). These considerations offer potential improvements in technology investment decisions relative to the criteria applied by the firm focused exclusively on the present, $R^k(S_t) > I_k$.

It is also insightful to contrast these decision rules with those used in the absence of temporal and spatial myopia. As elaborated in the previous section, the nonmyopic firm makes technology investments based on: $\max\{H(S_0) - I_1 - I_2, G_1(S_0) - I_1, G_2(S_0) - I_2, 0\}$. Relative to this ideal, 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 quite possible. The potential for errors due to synergistic and nonsynergistic technologies persists, regardless of the time horizon.

Interestingly, it is not necessarily the case that a firm with only spatial myopia would outperform a firm operating under both temporal and spatial myopia. It is possible that the biases associated with temporal and spatial myopia offset one another. Eliminating one form of myopia may not improve investment decisions if the other form of myopia persists. Investments made without temporal myopia—based on criteria (10a) and (10b)—do not necessarily outperform those combining both forms of myopia—using (12), (13a) and (13b), or even investments by the firm focused only on the present.

To understand this claim, consider the nature of the errors associated with temporal myopia and spatial myopia. Temporal myopia can produce Type I errors if subsequent maintenance and redeployment costs are high relative to initial investment costs. Alternatively, if maintenance and redeployment costs are low relative to initial investment costs, Type II errors can occur. Spatial myopia can result in underinvestment if technologies are complementary and overinvestment if technologies are incompatible. Figure 1 presents the combined effects of spatial and temporal myopia. Two of the combinations result in reinforcing errors. In such cases, correcting for one form of myopia could enhance initial investment decisions (i.e., reduce the likelihood of either Type I or Type II investment errors). However, for two of the combinations, the effects of spatial and temporal myopia offset one another. In these cases,

	I_k Relative to m_k and c_k: Low	I_k Relative to m_k and c_k: High
Complementary	Offsetting	Reinforce Type II Error
Incompatible	Reinforce Type I Error	Offsetting

Figure 1. Error patterns combining spatial and temporal myopia

correcting for just one form of myopia increases the likelihood of errors.

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 decisions. Whereas Levinthal and March emphasized overlooked substitute technologies in their discussion of spatial myopia, we considered overlooked interactions among technologies available to the firm.

In the absence of temporal myopia, the results are straightforward. Type I errors can only occur if both technologies are acquired and they are incompatible. Nonmyopic foresight eliminates any other possibilities for Type I errors, but does not eliminate the possibility of underperforming the optimal deployment strategy. Failure to recognize synergies can lead to Type II errors.

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

This study 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' (Levinthal and March, 1993: 103). Even simple knowledge inventory problems become challenging as managers attempt to think about the future and interactions among technologies.

A key insight motivating this study is that real option theory provides a framework for advancing our understanding of the management of knowledge inventories. Kulatilaka's contributions (Kulatilaka and Marcus, 1988; Kulatilaka and 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 research direction, 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. We know of only three published 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 purchase and exercise decisions.

Our analyses motivate some specific hypotheses regarding the management of knowledge inventories. These are summarized in Tables 1–3. Table 1 points out the variables affecting the likelihood of acquiring additional technologies for a firm's

Table 1. Variables affecting technology acquisitions[a]

	Temporal myopia		
	Current state uncertainty	No foresight	Foresight
Initial revenue	+	++	+
Initial investment cost	−−	−−	−
Switching cost[b]	0	−−	−
Reverse switching cost[b]	0	0	−
Maintenance cost for preceding technologies	0	−−	−
Maintenance cost for new technology	0	0	−
Disposal cost	0	0	−
Environmental instability	0	0	+
	Spatial myopia		
	No foresight	With foresight	No myopia
Initial revenue	++	+	+
Initial investment cost	−−	−	−
Maintenance cost for new technology	0	−	−
Redeployment cost	0	−	−
Disposal cost	0	−	−
Synergies	0	0	+
Environmental instability	0	+	+

[a] −−, strong negative effect; −, moderate negative effect; 0, no effect; +, moderate positive effect; ++, strong positive effect.
[b] 'Switching cost' and 'Reverse switching cost' refer to the costs of switching to the new technology and switching back to an alternative, respectively.

Table 2. Variables affecting switching between technologies[a]

	Temporal myopia		
	Current state uncertainty[b]	No foresight	Foresight[c]
Incremental revenue	0	++	+
Switching cost	0	−−	−
Incremental maintenance cost	0	−−	−
Reverse switching cost	0	0	−
Environmental instability	0	0	+

[a] −−, strong negative effect; −, moderate negative effect; 0, no effect; +, moderate positive effect; ++, strong positive effect.
[b] Under current state uncertainty, only a single technology is acquired, making switching impossible.
[c] This column offers the signs for any degree of foresight. Even single-period foresight results in consideration of all of the relevant variables. This can be seen in decision rule (9) in the 'Limited foresight' section.

Table 3. Variables affecting idling and redeploying technologies[a]

	Spatial myopia		
	No foresight	Without temporal myopia	No myopia
(a) Likelihood of idling technologies			
Current revenue	−−	−	−
Maintenance cost	−−	−	−
Redeployment cost	0	−	−
Probability of state reversion[b]	0	−	−
Synergies	0	0	−
(b) Likelihood of redeploying technologies			
Current revenue	++	+	+
Maintenance cost	++	+	+
Redeployment cost	−−	−	−
Probability of state reversion[b]	0	−	−
Synergies	0	0	+

[a] −−, strong negative effect; −, moderate negative effect; 0, no effect; +, moderate positive effect; ++, strong positive effect.
[b] 'Probability of state reversion' requires an explanation. The more likely is a return to the favorable state for that technology, the less likely it is that the firm will idle the technology. The more likely is a return to the unfavorable state, the less likely is redeployment.

knowledge inventory. Table 2 indicates the variables affecting technology switching, as discussed earlier in the section on temporal myopia. Table 3 shows the variables affecting idling and redeploying technologies, as elaborated in the section on spatial myopia. Variables not considered by managers (indicated by 0) and variables given undue emphasis (++ and −−) point to the sources of technology investment and deployment errors.

Consider first some implications from our analysis of temporal myopia. We showed that the more limited the time 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.[11] Initial technology acquisition is strongly influenced by the observable initial investment required and, to a lesser extent, the probable payoff (which can only be stated as an expected value, not with certainty).[12] Because only a single technology is acquired, no switching occurs.

It is widely recognized that a short-term focus on current performance is likely to result in underinvestment relative to foresightful decision making (see, for example, Laverty, 1996). However, in criticizing management for thinking short term, we neglect the positive aspect that Type I errors become highly 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 network externalities leading to increasing returns (see, for example, Arthur, 1994; Dierickx and Cool, 1989), we demonstrated how path dependency results from temporal myopia. This occurs because managers who focus on the short term fail to appreciate the full value associated with technological flexibility over longer time horizons. This perspective emphasizes the implications of managers' bounded rationality rather than the behaviors of consumers and 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' (Conner, 1988; Lerner, 1997) than on 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 managers' cognitive limitations.

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., $Pr(S_{t+1} = 1|S_t = 1) > Pr(S_{t+1} = 2|S_t = 1)$ and $Pr(S_{t+1} = 1|S_t = 2) > Pr(S_{t+1} = 2|S_t = 2)$, then forward-looking firms are less likely to invest in alternative technologies. Hence, as shown in Table 1, the contention that the breadth of a firm's knowledge inventory increases with environmental instability depends on the foresightfulness of managers. Furthermore, for foresightful firms, the higher the switching and maintenance costs, the smaller the knowledge inventory, for a given level of environmental instability.

Moving from a focus on the current period to single-period foresight, the behavioral decision rules regarding technology acquisition and switching became 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 multiperiod 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 from normative

[11] Heiner's approach has been criticized (see Bookstaber and Langsam, 1985; Driver, 1992; Garrison, 1985; 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.

[12] Under uncertainty about the current state, initial revenues are uncertain. As such, Table 1 shows that managers place a greater emphasis on initial revenues when the current state is known but there is no foresight than under current state uncertainty.

decision rules using dynamic programming. As shown in Table 2, firms switching among alternative technologies should consider not only switching costs, but also the difference in maintenance costs among alternative technologies (rather than the absolute magnitude of the maintenance costs). 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 technology 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 lower portion of Table 1 summarizes the hypothesized effects on acquisitions of new technologies under spatial myopia—with and without temporal myopia. Apart from the potential errors in technology acquisition, spatially myopic firms may fail to realize their full potential value because their deployment strategies are suboptimal.

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. For synergistic technologies, Type II errors are likely, whereas for incompatible technologies, Type I errors are likely. As summarized in Figure 1, these investment biases associated with 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. Correcting cognitive biases requires simultaneously lengthening managers' time horizons and considering technology interactions.

These observations, together with the findings summarized in Tables 1–3, allow us to make some practical observations for managers. The signs in Table 1 indicate that managerial decision rules under various forms of temporal and spatial myopia get the signs of some key relations correct. Under myopia, managers err in (1) the weights they assign to decision criteria and (2) their neglect of the full set of relevant variables. Hence, we can affirm that managers' heuristics are useful despite biases and omitted variables. However, our analysis of temporal myopia indicated that even modest extensions of the time horizon considered by managers can reduce errors due to oversight (i.e., omitted variables). When temporal and spatial myopia occur together, attacking both simultaneously can enhance decision making. Decision support tools based on the conceptual frameworks provided by real option theory could help to reduce knowledge inventory management errors.

Tables 1–3 also provide testable relations for future investigation. Research involving hypothetical technology management decisions is one possible direction for future studies. Researchers could devise investment choices involving multiple technologies and time periods to determine the cognitive limits of decision-makers acting individually or in groups. It would be interesting to know whether some managers are more temporally or spatially myopic than others, and the trade-offs when allocating scarce attention across temporal and spatial considerations. Behavioral simulations would allow for unambiguous determination of whether actual technology investment decisions deviate from ideal knowledge inventories and the nature of the errors (Type I or Type II). Of course, such simulations are limited to the extent that they exclude relevant contextual variables associated with decision making in real-world organizations (see Gist, Hopper, and Daniels, 1998).

Following the explanations offered earlier, it should be possible to develop operational measures of firms' knowledge inventory components. Such measures would identify the technological, strategic, or operational alternatives available to firms. Researchers could examine the acquisition of additional technologies over time or the relative size of knowledge inventories across firms. Conjectures regarding the types of myopia affecting a firm's knowledge inventory investment decisions could be tested by examining patterns in the magnitudes, signs, and significances of coefficients on proxies for the Table 1 explanatory variables. Tables 2 and 3 motivate research on switching among available technologies, as well as idling and redeploying a single technology. Such research could advance our understanding of organizational flexibility and could link cognitive considerations to organizational performance.

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