A REAL OPTIONS LOGIC FOR INITIATING TECHNOLOGY POSITIONING INVESTMENTS

RITA GUNThER MCGRATH
Columbia University

In this article I extend real options theory to technology positioning projects and specify how the relationship between boundary conditions and uncertainty influences the value of a technology option, as well as the appropriate timing of its exercise. I also take a strategic perspective on uncertainty itself, concluding that option value can be amplified by investments to shift boundaries, ideally in ways that are idiosyncratic to the firm.

Conventional valuation and budgeting techniques show their limitations when one applies them to investments requiring substantial commitment under conditions of significant uncertainty, such as investments in technology (Dixit & Pindyck, 1994). Although some scholars suggest real options theory as an alternative conceptual route of attack, its application to strategic technology positioning problems merits further development, which is my objective in this article (Bettis & Hitt, 1995; Bowman & Hurry, 1993; Mitchell & Hamilton, 1988; Trigeorgis, 1993).

In this article I extend real options concepts in two ways. First, I develop theory specifying how the relationship between boundary conditions and uncertainty influences the value of technology options, as well as the appropriate timing of their exercise. Second, I take a strategic perspective on uncertainty itself, arguing that value can be amplified by investments to shift boundaries, ideally in ways that reduce uncertainty idiosyncratically.

IDIOSYNCRATIC REDUCTION OF UNCERTAINTY AND RENTS

In strategic management capturing "rents" is a key performance objective, where the term represents excess profits that do not immediately induce a competitive response (see Alchian, 1991). One obvious way in which technologies generate rents for a firm is through monopoly, as with patented drugs. Even though competitors can observe and understand

Four anonymous Academy of Management Review reviewers offered valuable commentary. I much appreciate suggestions by Arnold C. Cooper and Ian C. MacMillan and comments by Neil Doherty, and I gratefully acknowledge the financial support of the Strategic Technology Assessment Research (STAR) Program of the Sol C. Snider Entrepreneurial Center at the Wharton School.
why the firm is successful, they are prevented by formal appropriability regimes from being able to mount an effective attack.

Somewhat more subtle are situations in which perfect competition is thwarted by the use of firm-specific routines (see Nelson & Winter, 1982, and Peteraf, 1993). Productive routines in technology are sometimes lucky accidents (Barney, 1986), but they also can reflect learning, in which those in a firm gain greater understanding of how to influence action-outcome relationships (Cheng & Van de Ven, 1996). In either case, knowledge and insight asymmetries can emerge by virtue of the experiential and path-dependent nature of the development process (Dierickx & Cool, 1989), resulting in different firms having different uncertainty profiles. Investments in development are attractive, by implication, when results idiosyncratically improve the relative uncertainty a firm faces in ways that can be kept firm specific (Amit & Schoemaker, 1993). My argument builds on these ideas to suggest constructs that can idiosyncratically influence both uncertainty and, consequently, the value of a technology option.

TECHNOLOGY POSITIONING PROJECTS GENERATE REAL OPTIONS

Real options theory scholars seek to understand classes of investment decisions having a structure similar to financial options contracts but for which the assumptions made in valuing financial options do not hold. The distinguishing characteristic of an options approach lies in firms making investments that confer the ability to select an outcome only if it is favorable.

Price and Value of a Technology Option

Financial options models rely on several core assumptions to arrive at an option price. The following are among the most important: the underlying asset on which the option is written must be priced, this price must be known, and the asset must be continuously tradable (Black & Scholes, 1973). The more volatile the price of the underlying asset, the more valuable the option becomes, as potential positive returns are greater, although potential losses are limited to the price of the option. These models cannot be applied to pricing options created through investment in technology positioning projects, for their core assumptions do not hold. For instance, the price of an underlying technology asset is not known, and it may not be continuously tradable.

In other respects, however, technology options have important similarities to financial options. The "price" of a technology option is the cost of development (which may occur in sequential stages). Completing the development of the technology creates an asset, consisting of the underlying right to commercialize the technology. "Exercise" of such an option involves the further investments needed to commercialize the technology (which may also occur sequentially). The option also may be "traded"—for instance, by being licensed out or spun off. In this regard the option is like
an American call: it can be exercised or traded any time after technology development is completed, or not at all. Completing commercialization creates another asset, which is the underlying right of the firm to extract returns from the exploitation of the now-commercialized technology (Kester, 1981).

Just as an investor may elect not to strike a financial option and lose only the amount of the options contract, a firm may elect to stop investing and limit losses to the sunk costs associated with the discontinued project. And, just as the value of a financial option increases as the price volatility of the underlying asset increases, so the value of a real technology option increases as the variance of the expected value of net revenues minus commercialization cost increases. The greater the expected variance in net operating revenues less commercialization costs, the higher the possible value of the underlying asset, although possible losses are limited.

Factors influencing price volatility therefore can be seen to influence the value of a financial option, and factors influencing variances similarly influence the value of a real technology option. The greater the uncertainty with respect to net revenues and costs, the more likely it is that large variances will be anticipated. This brings us to the critical role that the nature of uncertainty plays in establishing the value of a real technology option.

Technical and External Uncertainty, Timing, and Option Value

In their 1994 book, Investment Under Uncertainty, Dixit and Pindyck distinguish between two forms of uncertainty: “technical” uncertainty and “input cost” uncertainty. Technical uncertainty relates to the likely costs and probabilities of accomplishing technical success; a firm reduces this type of uncertainty only through investment. Technical uncertainty creates pressure on the firm to invest immediately. Delays, at best, incur a discounting penalty and, at worst, expose the firm to the risk of competitive preemption. Positive feedback effects to scale, path dependence, and network externalities may simply lock out late entrants (see Arthur, 1994). Later entry also can subject the firm to what Dierickx and Cool (1989) term “time compression diseconomies,” relative to early movers. Early, aggressive entry in the face of technical uncertainty can be critical. However, moving early can subject a firm to a punishing array of difficulties, including the bearing of the costs of infrastructure, the appropriation of rents by owners of needed cospecialized assets, and other aggravations (Lieberman & Montgomery, 1988).

These timing dilemmas, when a firm faces technical uncertainty, significantly increase the benefit to the firm of adopting an options approach for two reasons. First, although the volatility of new markets is greater than that of established markets, options have greater value in such markets. Second, viewing the technological challenge as a series of
sequentially exercised options accommodates a milestone-oriented, iterative management process. This simultaneously permits project redirection, advances learning, and permits investment to be discontinued at the earliest possible time, conserving the firm's precious resources (Bowman & Hurry, 1993; Eisenhardt & Tabrizi, 1995).

A second form of uncertainty, which Dixit and Pindyck (1994) term "input cost" uncertainty, relates to factors exogenous to the firm. No amount of investment makes a difference in this form of uncertainty, which creates pressure on the firm to delay investment until information is revealed with the passage of time.

Yet a third form of uncertainty exists, lying between the two forms Dixit and Pindyck identify. It is present when sources of uncertainty are largely "external" to the firm (in other words, not technical in nature) but can be influenced by strategic action. If it is possible for the firm to act as an agent of endogenous change, it may seek to shape contingencies in its favor. This gets to the heart of the strategic component of the use of a real options framework. The form uncertainty takes shapes the boundary conditions within which option value may be estimated and strategic action taken.

**External Uncertainty and the Value of the Option to Wait**

In determining whether a firm can take strategic action, one must first assess temporal truncation—where the passage of time alone brings uncertainty to an end. For example, let us consider a hypothetical investment by a firm in technologies for pollution control. Suppose that adoption will occur only if environmental control regulations contain certain provisions. Developing the technology will cost the firm an estimated $10 million; it is equally probable that the net present value of commercialization costs will be either $100 million or $50 million. The net present value of revenues under favorable regulation (a 50 percent probability) will likely be $180 million. Absent favorable rules (a 50 percent probability), revenues are expected to be $0. The decision tree for this investment under risk decision\(^1\) is presented in Figure 1. The expected value of the project is:

\[
0.5(-100 + 0.5 \times 180 + 0.5 \times 0) + 0.5(-50 + 0.5 \times 180 + 0.5 \times 0) - 10 = 5 \text{ million}
\]

or an expected profit of $5 million. The firm should immediately invest under conventional net present value rules.

When we recall, however, that the options approach allows a firm to select an outcome only if it is favorable, a rather different picture emerges. What we have here is a situation in which uncertainty with

\(^1\) Since this model utilizes probability estimates, this is a decision in a risk situation rather than a decision under uncertainty.
respect to the pending regulation will be truncated by the passage of time. Eventually, open issues will be resolved. Let us say the firm recognizes this and elects to hold off on further investments until the regulatory uncertainty is temporally truncated. If, for simplicity, we assume that the firm’s discount rate is 10 percent and that the regulatory issue will be decided in 1 year, the expected value of such a “wait-and-see” strategy is:

$$0.9(0.5[180 - 100] + 0.5[180 - 50] - 10] + 0.5(-10) = 38.25 \text{ million}$$

The presence of temporally truncated uncertainty increases the value of holding the option, as opposed to exercising it, since it decreases the value of immediate investment. The firm should simply wait and see. If we apply the concept of external uncertainty to this problem, however, another, less obvious approach emerges. Let us suppose that the firm can conceive of actions that will help shape emergent rules in its favor. In such a situation, it may elect to hold its technology option but instead may make strategic investments on other fronts. Such alternative investments, if successful, amplify the value of the underlying claim to commercialize, prior to commencing commercialization.

**Amplifying Preinvestments**

In the hypothetical example given above, uncertainty both constrains the positive potential of the project and establishes an expiration date for
options on the technology. The option will only be "in the money" if new regulations are adopted, which will happen at some future point. Let us suppose, instead, that the firm pays a group of lobbyists to help push through favorable regulation (MacMillan, 1978). If the lobbyists could guarantee the immediate adoption of favorable rules, the firm would capture $180 - (0.5 \times 50 + 0.5 \times 100) - 10 = $95 million in expected value, versus the $38.25 million expected previously. By implication, the firm could spend up to $56.75 million on a lobbying strategy having a 100 percent chance of immediate success, which theoretically justifies an expenditure of $5 million or so with a strategy having only a 10 percent chance of success.

As a thriving lobbying industry suggests, it may behoove firms to maximize the value of their options by influencing key legal boundary conditions rather than by investing in technology per se. When it is possible for firms to make amplifying preinvestments, these preinvestments create a context in which the technology can flourish, which has the effect of increasing the value of the underlying technology asset and the value of the option.

**Effects of Boundary Conditions on Variance of Net Returns and Option Value**

Variance for technology options behaves in a way similar to volatility in financial options. The greater the variance in net revenues that might be accessed by commercializing the technology, the greater the option value. By implication, to the extent that variance of expected returns is constrained, so too is the potential for gain. This depresses the value of the option. When we relax the constraints, however, as with an amplifying preinvestment, we increase the value of the option.

If the variance of the returns is \( \text{var} \, \pi \), the variance of net revenues from operations is \( \text{var} \, r \), and the variance of commercialization costs is \( \text{var} \, c \), then \( \text{var} \, \pi = \text{var}(r - c) = \text{var} \, r + \text{var} \, c \). If \( E[r] \) is expected net revenues and \( E[c] \) is expected commercialization costs, this leads to two distinct cases:

1. **Case 1:** \( E[r] > E[c] \): \( \text{var} \, r > \text{var} \, c \). Here, the upper limit of \( \text{var} \, \pi \) is determined by \( \text{var} \, r \). Amplifying strategies that relax any boundary conditions suppressing the variance of net revenues will increase the value of the option.
2. **Case 2:** \( E[r] > E[c] \): \( \text{var} \, c > \text{var} \, r \). Here, the upper limit of \( \text{var} \, \pi \) is determined by boundary conditions that significantly obstruct lower limits on commercialization costs. In other words, the boundary conditions cause commercialization costs to be inordinately high. In this case, amplifying strategies that reduce the variance of commercialization costs, \( \text{var} \, c \), to below the variance of net revenues, \( \text{var} \, r \), will increase the value of the real technology option.

This suggests an important implication for the application of real options theory to technology investments—namely, that valuation of a
technology option cannot be conducted in isolation of potential amplification opportunities. Amplifying strategies, in turn, cannot be pursued without taking into account the relations among revenues and costs. The value of a particular technology option to a particular firm, therefore, is deeply embedded in the strategic context of that firm and cannot be considered apart from it. Practically, this suggests that pursuing technology decisions without considering other facets of the overall strategy could lead to significant suboptimality, particularly if the boundary conditions shaping uncertainty lend the situation to amplifying preinvestment opportunities.

This brings us to a discussion of the nature of key boundary conditions that influence the uncertainty profile of a technology option and the associated amplifying preinvestments that could release these bounds to enhance the value of the option.

BOUNDARY CONDITIONS AFFECTING THE UNDERLYING CLAIM TO CUMULATIVE RETURNS FROM OPERATIONS

Here, I first take up case 1 situations, in which the objective is to determine whether boundary conditions set limits on the positive potential magnitude of var r. This is of particular concern for firms facing "hypercompetitive" (D'Aveni, 1994; MacMillan, 1988) environments, in which any rents flowing from successful commercialization will come under severe competitive pressures. Under such circumstances, to paraphrase Hobbes, conditions are brutal, exchanges nasty, and the duration of any competitive advantage short.

In order to justify taking out an option on a technology, a firm’s scale of cumulative rent streams from deployment of the asset must be large enough to recover initial investment in the face of attempts at appropriation. This recovery often is done in a compressed time frame. Two factors determine the scale of cumulative returns—the size of the rent stream and the length of time it can be sustained—each of which poses its own set of uncertainties. These factors and their determinants, as well as possible amplifying preinvestments, are summarized in Table 1. The relationships depicted in Table 1 represent proposed effects of uncertainty, strategies, idiosyncratic resources, and the value of the option.

Boundary Conditions and Uncertainty Regarding Size of Rent Streams

Uncertainty regarding demand. The idea that successful innovations should “satisfy some want” (Schmookler, 1966) long has been recognized as a core premise in the technology and innovation management literature (Kamien & Schwartz, 1975; Myers & Marquis, 1969; Mowery & Rosenberg, 1982; Scherer, 1979), for, absent want, there will be no demand. As Mowery and Rosenberg (1982) observe, however, ex ante clarity on
<table>
<thead>
<tr>
<th>Sources of Uncertainty</th>
<th>Contingent Factors that Bound Value of Option</th>
<th>Effect on Option Value</th>
<th>Opportunity for Amplifying Preinvestment</th>
<th>Opportunity for Deployment of Idiosyncratic Endowments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cumulative net revenues</td>
<td>Convexity and monotonicity of demand</td>
<td>Plus</td>
<td>Aggressive early moves that generate positive returns to scale</td>
<td>Reputation and track record that offer access to capital and other resources</td>
</tr>
<tr>
<td></td>
<td>Adoption speed uncertainty</td>
<td>Minus</td>
<td>Reduce obstacles to adoption, increase perceived attractiveness</td>
<td>Idiosyncratic customer linkages</td>
</tr>
<tr>
<td></td>
<td>Likelihood of blocking</td>
<td>Minus</td>
<td>Counterblocking</td>
<td>Institutional/collaborative relationships</td>
</tr>
<tr>
<td></td>
<td>Likelihood of expropriation</td>
<td>Minus</td>
<td>Negotiated environment</td>
<td>Idiosyncratic negotiating “stakes”</td>
</tr>
<tr>
<td>Sustainability</td>
<td>Likelihood of matching</td>
<td>Minus</td>
<td>Standard setting</td>
<td>Collaborative relationships</td>
</tr>
<tr>
<td></td>
<td>Likelihood of imitation</td>
<td>Minus</td>
<td>Development of appropriability regimes, collaborative arrangements</td>
<td>Collaborative relationships or membership in standard-setting bodies</td>
</tr>
<tr>
<td>Commercialization cost</td>
<td>Infrastructure requirements</td>
<td>Minus</td>
<td>Parallel or joint development</td>
<td>Exclusive control over critical contingencies or resources</td>
</tr>
<tr>
<td></td>
<td>Parallel technology development</td>
<td>Minus</td>
<td>Parallel or joint development</td>
<td>Preemptive alliance with leading partner</td>
</tr>
<tr>
<td></td>
<td>Cospecialized assets requirements</td>
<td>Minus</td>
<td>Parallel or joint development</td>
<td>Firm-specific, cospecialized assets or preemptive alliance with asset owner</td>
</tr>
<tr>
<td>Technology development cost</td>
<td>Spillover potential</td>
<td>Plus</td>
<td>Internal cross-fertilization</td>
<td>Competences and customer relations</td>
</tr>
<tr>
<td></td>
<td>Life-cycle effects</td>
<td>Minus</td>
<td>Membership in community technical organization</td>
<td>Preexisting standard-setting relationships</td>
</tr>
</tbody>
</table>
market demand is difficult to establish, particularly for very new technologies. Potential customers find it difficult to assess the value of a technology with which they have no experience. Under such circumstances, conventional market research often is not only inaccurate but actually can be misleading (von Hippel, 1988).

Although it may not be possible to estimate demand accurately, it may be possible to identify demand structures that are more or less attractive (recalling a philosophy for evaluating technologies proposed by Goodman & Lawless, 1994). If, for instance, potential applications of the technology have an underlying demand structure with properties of monotonicity and convexity, the technology asset’s value should be greater and so, too, should the value of the option.

For example, let us contrast the demand structure of a technology that would dramatically ameliorate the symptoms of a widespread, frequently recurring ailment, such as the common cold, with one that would cure a disease that afflicts 1 person in 100,000. In the first case, usage is repetitive and incidence widespread, suggesting both a greater potential mean and greater potential variance in demand than in the second case, in which there is but a single dosage required for a highly limited population. This suggests that one may be able to assess whether the potential variance of demand opportunities is vast or limited. Examples of factors signaling how attractive the structure of demand is include the following: whether there are many or few problems the technology might solve; whether problems that the technology might solve are widespread; and, if the problem is widespread, whether it is also growing, whether it recurs rather than is resolved, whether recurrence is frequent, and so on.

The more the demand structure suggests that demand over time will be monotonic and convex, rather than concave, the greater the potential mean demand, and, more important, the greater the demand’s potential variance, which increases potential returns and thus the value of the option.

When the firm can recognize and capitalize on advantages created by positive returns to scale, it may preinvest by setting the stage for aggressive early moves (Lieberman & Montgomery, 1988). Examples of such moves might include preemptively investing to secure network position or network commitments in industries with significant network externality effects (Conner, 1995). Similarly, an established firm may use such a firm-specific asset as a solid reputation with the financial community to idiosyncratically gain access to those resources (such as equity capital) that allow it to engage in an aggressive launch.

**Uncertainty regarding speed of adoption.** Slow adoption rates can limit cumulative returns significantly by delaying revenue inflows and reducing the time before alert competitors can compete away rent streams. The importance of speed of adoption has prompted a considerable number of scholars to assess the conditions under which diffusion is
likely to be rapid or slow (see Rogers, 1995). Slow appears to be the norm. Typically, both the innovating firm and its customers must establish a base of experience before widespread adoption occurs (Levinthal & March, 1993: 106). Factors that tend to delay adoption include whether and how much education or training is required to use the technology; whether adoption implies a significant change in usage patterns; whether there is a need for coevolved infrastructure; whether customers have significant sunk costs in older technologies; and whether customers perceive adoption as risky. Factors tending to increase confidence in rapid adoption include low risk to the potential customer, alignment between beneficiaries and buyers, and the likelihood of the firm establishing an early dominant design (Dewar & Dutton, 1986; Katz & Shapiro, 1985; Lieberman & Montgomery, 1988).

Slow adoption affects the scale of potential revenues in two ways. First, it delays the onset of revenue streams, with a concomitant discounting penalty. This reduces both the mean and variance of potential cumulative revenue streams. Second, slow adoption creates a period in which new competitors may enter in a competition for the dominant design, prompting expensive introduction of new product features (Anderson & Tushman, 1990). Alternatively, firms using established technologies have more time to react (Cooper & Smith, 1992). Slow adoption, in short, reduces the variance of cumulative returns and, consequently, the value of the option.

The adoption rate, however, may be amenable to an amplifying pre-investment strategy. To the extent that a firm can find ways to reduce the risks or costs to customers, or to demonstrate clear superiority over existing procedures, adoption can be accelerated. Capturing the support of what von Hippel (1988) refers to as “lead users,” achieving critical mass with a core group of distributors or with opinion leaders, and helping customers ease the transition (e.g., by providing backward compatibility) are all likely strategies for a firm.

Similarly, a firm may use firm-specific resources to execute these strategies, which offers the additional potential for firm-specific reduction in uncertainty. A firm’s past successful relationships, for instance, can create routine specificity between the firm and its groups of customers and suppliers—what Venkataraman (1990) terms its “transaction set.” Existing customers, other things being equal, more likely will adopt new technologies from existing suppliers than from unknown suppliers. As a history of trusting interactions reduces the perceived risk of purchasing the new technology, adoption can be accelerated (Block & MacMillan, 1993).

**Uncertainty regarding blocking.** “Blocking” refers to situations in which a firm is denied access to inputs, applications, customers, markets,

---

2. \( \text{var } x_t = \sum(x_t - \bar{x}_t)^2/n \). If \( x_{t+1} = \alpha x_t \), where \( 1 - \alpha \) is the discount rate, then \( \text{var } x_{t+1} = \alpha^2 \text{ var } x_t \), so \( \text{var } x_{t+1} < \text{ var } x_t \) if \( \alpha \) is less than 1.
or other business essentials by competitive or regulatory action. Since the variance of a sum is equal to the sum of individual variances, the total variance of the cumulative revenue streams is reduced by the variance of each individual blocked revenue stream.\(^3\) Thus, any point of blocking reduces the value of both the mean and the variance of revenues, therefore reducing the value of the option.

The dynamics of blocking have been discussed with respect to barriers to entry (Porter, 1980), preemptive behavior (Fudenberg & Tirole, 1985; Gilbert & Newberry, 1982), market power (Boulding & Staelin, 1990; Montgomery, 1985), foreign direct investments (Caves, 1971), pricing rivalry (Chen & MacMillan, 1992), and competitive signaling (Chen, Venkataraman, MacMillan, & Black, 1991). A common theme in these studies is that, consciously and with intent, a party external to the firm creates obstacles.

Studying this literature yields some interesting insights regarding the sources of likely blocking behavior. For example, those whose control over key influencers is threatened by the technology are likely to use this control to block adoption (MacMillan, 1978; MacMillan & Jones, 1986). Rivals with monopolistic or quasi-monopolistic market control further may block entry by interfering with access to suppliers, distributors, or key customers (Teece, 1986). Advocacy groups with an interest in preventing the adoption of the technology may impose explicit or subtle legislative, regulatory, or public opinion prohibitions with a blocking effect (Teece, 1986). Finally, those with a vested interest in preventing open competition may block access to geographic markets or may impose expensive conditions upon obtaining that access (Mowery & Teece, 1993).

If the danger of blocking is high, the value of the option can be amplified by the firm to the extent that it successfully can preinvest in counterblocking strategies prior to committing resources to the technology. The environmental technology example I referred to earlier reflects such a situation. Relevant idiosyncratic resources, as Table 1 suggests, are those institutional or collaborative relationships allowing a firm to uniquely eliminate the threat of blocking, ideally while preserving a blocked position for competitors.

**Uncertainty regarding expropriation.** Expropriation is related to blocking, in that the firm faces the threat of difficulty from powerful external players, but differs in its outcome. When blocked, a firm simply is denied access to critical resources and markets. Under expropriation, however, the firm is required to cede a portion of its rent streams, and, as the net revenues are reduced, so too is their variance.\(^4\)

---

\(^3\) Let \(x\) and \(y\) be segments with revenue variances of \(\text{var } x\) and \(\text{var } y\), respectively. If the variance of the combined segments is \(\text{var}(x + y)\), then \(\text{var}(x + y) = \text{var } x + \text{var } y\). This means that if segment \(x\) is blocked, the resulting variance of revenues is \(\text{var}(x + y) - \text{var } x\), which is less than the original total variance.

\(^4\) \(\text{var } x = \frac{\sum(x - \text{mean })^2}{n}\). If \(y = ax\), where \(a\) is the proportion of revenue streams not expropriated from the original revenue \(x\), then \(\text{var } y = a^2 \text{var } x\), and \(\text{var } y < \text{var } x\), if \(a < 1\).
The threat of expropriation may come from either governmental or interorganizational sources. Governments, for reasons of national interest, commonly place rent-sharing obligations on firms. These may take the form of requirements that technologies be made available to other firms, that local employees receive employment, and that the firm support infrastructure development or training programs, or they may involve outright commandeering of the firm's assets (Kobrin, 1982; Teece, 1986).

Interorganizational dynamics also can exacerbate expropriation. Discriminatory regulation or exclusionary business networks can inhibit innovators’ access to markets or can force them to disclose the technology (Cusumano & Takeishi, 1991). Entities other than the innovator can control some crucial aspect of the value chain and extract rents that might otherwise go to the innovating firm. Similarly, organized labor can extract a portion of rents.

With expropriation threats, the firm’s creation of a negotiated environment is an important amplifying strategy. To the extent that the firm can make favorable deals with potential expropriators prior to launching the technology, it may be able to amplify the value of its option. In fact, there is a real danger in not prenegotiating: the firm will find itself in a much weaker bargaining position after having made an irreversible technology investment. But when the firm is in possession of unique stakes desired by parties to the negotiation, it can potentially achieve an idiosyncratically superior arrangement.

Boundary Conditions and Uncertainty Regarding Sustainability of the Rent Stream

Uncertainty regarding matching. The problem of matching is one of equifinality. Rent streams are appropriated under matching—not through imitation but through substitution. Parallel efforts by both direct and indirect competitors may address the same needs and problems as the proposed technology. They may find a different path to a similar end. This has the effect of reducing the net revenues, relative to circumstances without the threat of matching, and it also reduces the variance of potential revenues. Probability of matching reduces the value of the option.\(^5\)

Although scholars have not paid much attention to it in the resource-based literature, matching raises questions regarding the value of idiosyncratic endowments. Unless others cannot mobilize their own idiosyncratic endowments to create equivalent value for customers, rents may still be competed away. The diffusion of graphical user interfaces is an example. Originated by the Xerox Corporation, these interfaces later were adopted by Apple Computer and subsequently embedded in the “Windows” products of the Microsoft Corporation. Although the hardware plat-

\(^5\) If \(x\) is the expected stream of revenues without matching, and \(y = ax\) is the reduced revenue stream with matching, then, as above, \(\text{var } y < \text{var } x\).
forms for each variant of the interface differed significantly, their utility, from the perspective of the end user, was similar.

The threat and likelihood of matching are influenced by three additional factors: (1) motivation and capacity of rivals, (2) customer immobilities, and (3) order of entry and lock-out effects. To the extent that capable competitors are threatened, motivation to match increases (Chen & MacMillan, 1992). Immobilities can be created when early-adopting customers must make investments to use the innovator’s products (imposing a cost to switch to another supplier), when transaction-specific learning creates reluctance to change to another way of doing things (Wernerfelt, 1985), when firms establish long-term contracts, or when customers are offered some form of incentive (such as a favorable discount) to remain with the innovating firm. Buyer immobility also can result from psychological costs. Firm reputation (Fombrun & Shanley, 1990), name recognition (Liebemer & Montgomery, 1988), and well-established relationships can create inertia as well. When positive feedback or network effects yield increasing returns to early movers, those making later attempts to match may never be able to overcome established, embedded technologies (David & Bunn, 1988; Katz & Shapiro, 1985).

As Rosenkopf and Tushman (1994) argue, one strategy for amplification consists of collaborative arrangements that set standards favoring the firm’s technology over competing technologies. To the extent that a firm is party to standard setting when others are not, this form of access can create an idiosyncratic advantage.

Uncertainty regarding imitation. Unlike blocking, expropriation, or matching, imitation truncates revenue streams by increasing supply of a product or service, thereby decreasing its rarity and, thence, price (Barney, 1991). Imitators doubly disadvantage the innovating firm in that their cost to imitate is often a fraction of the cost to originate (MacMillan, McCaffery, & Van Wijk, 1985; Mansfield, 1988). As in the case of matching, this has the effect of reducing both the mean and the variance of potential revenues and, concomitantly, reducing the value of the option.

One solution to the problem of imitation is for a firm to take advantage of “tight” appropriability regimes for such organizational assets as patents, trademarks, and copyrights (Ghemawat, 1984; Rumelt, 1987). It is important to note that not only the existence of the regime, but its enforcement as well, is necessary for effective prevention of imitation. Collaborative preinvestments in reinforcing appropriability regimes thus can amplify later technological breakthroughs. Firms engaging in network strategies, strategic alliances, joint ventures, and collaborative research programs may find that these relationships, too, can increase rent potential by virtue of quasi-monopolistic collaborative strategies (Koh & Venkatraman, 1991; Shrader, Lincoln, & Hoffman, 1989). Despite the fact that rents are shared, collaborative strategies are one of the few mechanisms, in an increasingly global competitive environment, limiting competition and delaying the appropriation of rent streams.
A firm's uncertainty regarding the size of cumulative net revenue streams affects the streams' expected variance and, thus, option value in case 1 situations, where \( \text{var } r \) is greater than \( \text{var } c \). Let us turn next to uncertainty with respect to commercialization costs, which influence the value of the option for the case 2 situation, where \( \text{var } c \) is greater than \( \text{var } r \).

**BOUNDARY CONDITIONS AND COMMERCIALIZATION COSTS**

Scholars writing about commercialization of technology identify three broad categories of costs: (1) investments in production assets, (2) infrastructure development investments, and (3) costs to develop parallel technologies and cospecialized or complementary assets (Mansfield, 1988). They address extensively the estimation of production asset costs, concluding generally that the more ambitious or asset intensive the project, the more expensive it is likely to be (Greer & Moses, 1992). Less obvious considerations apply to the second and third categories, because they often either pose unforeseen costs or promise unforeseen benefits to the firm. The higher the anticipated variance is of commercialization costs, the lower the value of the option will be; also, more preinvestment relaxing these boundary conditions will enhance the value of the option.

**Uncertainty regarding accessibility to necessary infrastructure.** Firms may incur significant and unexpected costs to create infrastructures and coevolved systems supporting the delivery, sale, and servicing of their outputs (Itami, 1987). Necessary but often unanticipated usurpers of corporate resources, infrastructure costs can include creation of physical infrastructure, such as distribution, service, communication, and transportation systems; creation of social infrastructures, including commonly accepted business practices or standards (Rosenkopf & Tushman, 1994); and creation of a human capital infrastructure (Becker, 1964). Clearly, to the extent that the availability of such infrastructures is uncertain now or in the future, the expected costs of commercialization and their variance will be greater, setting a lower boundary on the value of the option.

To the extent that infrastructure development is either not necessary or can be completed collaboratively prior to the completion of technology development, the variance in commercialization cost, \( \text{var } c \), will be reduced and the value of the option amplified. There is also a role for firm-specific resources. If the firm can capture an exclusively advantaged position with respect to critical contingencies or infrastructure (e.g., by obtaining exclusive rights of way), it may shut out competitors' access to the infrastructure and preserve a position of privilege.

**Uncertainty regarding availability of parallel technologies.** A second broad area of investment necessary in commercializing a technology has to do with the uncertainty regarding the development of parallel tech-
nologies that may be needed to create demand or to use the target technology effectively. Software for personal computers and content for home video and game systems illustrate situations in which the sale of one technology is dependent upon the parallel development of another. Creating such complementary assets can be both costly and uncertain, increasing var c.

Alliances have a role to play here, as do such technology-sharing arrangements as research and development consortia. To the extent that the firm itself possesses firm-specific parallel technologies and cospecialized assets, it can expect to uniquely reap the benefits of combining them with the new technology. Therefore, the greater the potential is to deploy existing parallel technologies or uniquely owned cospecialized assets in conjunction with the proposed technology, the greater the value of the technology option will be. We must note, however, that this argument can apply in reverse: to the extent that existing technologies are unlikely to be valuable in future commercialization, firms may find themselves facing competence-destroying innovations (Tushman & Anderson, 1986), competence traps (Levitt & March, 1988), and disruptive technologies (Christensen & Rosenbloom, 1995).

Figure 2 illustrates how the relationship between the underlying claim to cumulative returns from operations and the cost of commercialization influences the value of the underlying claim to commercialize. Investment makes sense only when this value exceeds the "price" the firm must pay to create the option. Price, here, is considered to be the cost to develop the technology.

![FIGURE 2](image-url)

Factors Influencing the Value of a Technology Positioning Option

- Value of Underlying Claim to Cumulative Returns from Operations
  - Per period size of revenue stream
  - Structure of demand
  - Speed of adoption
  - Blocking potential
  - Expropriation potential
- Sustainability of revenue stream
  - Matching potential
  - Imitation Potential

Cost of Commercialization
- Infrastructure requirements
- Parallel technology requirements
- Cospecialized asset requirements

Value of Underlying Claim to Commercialize

Cost of Technology Development = Option Price
- Spillover effects
- Technology
- Life-cycle status

Value of Technology Option
FACTORs INFLUENCING PRICE OF THE OPTION: DEVELOPMENT COST

In this model the cost of the technology, other than the direct cost of development, stems from two important components. The first is the extent to which developing a technology offers a firm positive “spillovers” (Itami, 1987: 118). The second is the extent to which the technology is in the early stages of the technology cycle.

Spillover effects. As scholars have argued in the learning literature (Cohen & Levinthal, 1990), investments intended to create new knowledge for the firm often have important spillover effects, which, to some extent, explains why firms engage in such practices as “informal know-how-trading” (von Hippel, 1987) or scientific collaboration (Hagedoorn, 1993). A firm often begins such activities with the intention of not only acquiring new knowledge relevant to developing technologies but also of improving the base business. Itami (1987) discusses this dynamic in depth. If, he argues, the new insight and new capabilities the firm develops in the pursuit of new technologies can be used to enhance the attractiveness or lower the cost of existing products, the firm’s cost of development may be defrayed and rent streams, as a whole, enhanced.

A firm amplifies spillover benefits in one way when it utilizes the developing technology to enter modest markets with the intention of using these as a springboard to target other markets when the technology is sufficiently well developed. The strategy the firm uses may emphasize incremental product introductions to capture “adjacent” markets as stepping stones to a more ambitious strategy, or it may emphasize the disruption of previous technology barriers to open entirely new opportunity spaces (Itami, 1987; McGrath, MacMillan, & Tushman, 1992). A common thread in both approaches is that the firm deliberately uses entry into specialized subfields or modest new markets to garner experience. Thus, the greater the potential for early entry into commercial markets, the more certain one can be that costs can be recovered en route—hence, the lower the “price” of the technology option. The extent to which the firm exploits existing idiosyncratic competences and current idiosyncratic relations with customers significantly enhances the potential for early spillover benefits and creates idiosyncratic opportunities to reduce the cost of the real option.

A second form of spillover can occur when a firm can envisage selling or trading the option prior to commercialization. In this case, the firm may be able to generate returns when others perceive the option as valuable, without incurring the costs of exercise.

Technology life-cycle status. Several scholars have shown that technology cycles have significant effects on technology strategies in that they influence the basis of competition and the nature of the uncertainties faced (Anderson & Tushman, 1990; McGrath et al., 1992; Tushman & Anderson, 1986). During periods of incremental change, learning is “exploited”
(March, 1991), and positions of advantage tend to be reinforced. During periods of ferment and disruption, investments in "exploration" must be made, and incumbent positions are at risk.

In incremental, evolutionary technology development, firms often innovate within the context of a dominant design (Tushman & Anderson, 1986), meaning that key dimensions of merit in the marketplace have been established, the firms' customers have been educated, and their coexisting technologies share a common architecture. Each of these acts to reduce development costs. When disruptive technologies are introduced, however, firms often need to make investments to identify what attributes of the technology will be crucial, to acquire or train people in the new field, to communicate the benefits of the technology, and to develop parallel or supporting technologies.

Interestingly, the uncertainty of eras of ferment makes the use of technology options more attractive, as hedges against placing the wrong technology bets. Paradoxically, however, creating the option (by developing the technology) is apt to be more expensive. Because dimensions of merit are unclear, a firm may anticipate expensive design variations, experimentation, investment in assets of questionable future use, and investments to create or prompt development of parallel or complementary technologies, as well as considerable community-level coordination costs (Rosenkopf & Tushman, 1994). Therefore, earlier in the technology cycle, costs are greater and more uncertain than they are at later points. At the same time, possible gains motivate firms to take out these options.

It may pay the firm handsomely to invest in participation in what Rosenkopf and Tushman term "community technological organizations" (1994: 410), which help shape the standards and specifications for an emerging technology, as well as in the technology itself.

MODELING THE VALUE OF OPTIONS ON TECHNOLOGY

As Figure 2 shows, the value of an option on a technology can be described in terms of three contracts: (1) the cost to develop the technology, which is equivalent to the price of taking out the technology positioning option; (2) the cost of commercialization; and (3) the value of the underlying claim to cumulative returns from operations. As in financial options, greater uncertainty tends to increase the attractiveness of making an options investment, provided the firm can contain possible losses.

An option is also increasingly attractive if the firm can approach it through sequential development so that incurring the cost of development for one stage does not irreversibly commit the firm to the next stage of development. Even when the amount of potential losses on technology development cannot be predicted, expenditures to reduce technical uncertainty (which only investment will resolve) may still be warranted if sequencing is possible.

Uncertainty also suggests a role for both strategy and for idiosyn-
ocratic resource endowments. I treat the uncertainty profiles of firms here as heterogeneous, suggesting that a strategic objective for investments in technology is to reduce uncertainty for oneself, without similarly reducing it for competitors. To the extent that investments in a technology positioning project show promise of drawing from firm-specific skills, assets, and routines, the firm may further be able to idiosyncratically reduce uncertainty in ways that are specific to it and inappropriable by competitors.

In situations where the nature of uncertainty the firm faces for a project is such that no amount of investment can reduce it, but the uncertainty will be truncated temporally, the firm may opt to postpone the option. Where there is "external" uncertainty, however, the firm may take strategic actions to amplify the value of the option. I identify and summarize opportunities for deploying both amplifying preinvestments and idiosyncratic resource endowments in Table 1.

**DISCUSSION**

One of my objectives in this article was to develop a parsimonious, yet comprehensive, model of the forces influencing the value of a technology option, while recognizing that the assumptions used to value financial options cannot be made for real options. Although not exhaustive, the framework I present in Figure 2 integrates previous research on technology strategy and uncertainty to articulate whether, and when, initiating an option shows the potential to gain the firm access to future rents.

My treatment here of uncertainty and firm-specific uncertainty reduction specifically and unambiguously integrates real options models, technology assessment, and strategic management theory. It makes clear, for example, that existing resource endowments are apt to be important for technology positioning when they allow a firm to idiosyncratically reduce critical uncertainties in ways that are not obvious to competitors. By implication, it also suggests that endowments that either systematically create an uncertainty disadvantage for the firm or that are no longer differentiated with respect to competition have little strategic value in the technology positioning decision. A legacy computer system, for instance, which certainly qualifies as a part of a firm's heritage, may prove more of a hindrance than an asset if it is incapable of helping the firm resolve critical uncertainties in a timely way.

The model I present also suggests that appropriate strategic action with respect to a given technology actually may have less to do with the technology than with other factors "external" to it and often to the firm. Not only is a firm sometimes better served by waiting than by proceeding with an investment, but it may extract maximum value by proceeding along a different strategic front. The argument I summarize in Table 1 also suggests specifically which forms of strategic action may be most appropriate under different boundary conditions.

Hence, this view of technologies as options links the technology strat-
egy of a firm directly with its broader business, political, and social strategies. For example, by arguing that, in some cases, a firm’s technology development should pause while contextual and regulatory actions are taken to create inappropriability, I directly connect in this framework such institutional-level issues as legitimacy with competitive strategy. This motivates a view of technology that does not exist in isolation but, rather, is one element in an overall strategy to capture rents, clearly embedded in a competitive and institutional context.

Scholars have not yet introduced the concept of amplifying preinvestments to create an appropriate context in the real options literature. The framework I present here both introduces this idea and suggests when and how such amplifying preinvestments can be of strategic use to a firm. Further, I suggest approaches to estimating the value, and therefore the acceptable level of investment, in such amplifying strategies.

IMPLICATIONS FOR FURTHER RESEARCH

Operationalization and subsequent empirical testing clearly are indicated in terms of further research. Moving toward the development of both direct and indirect measures is the next logical step. Direct measures might include such variables as demographics to anticipate growth in demand, interest group communications and legislative/regulatory agendas to measure blocking potential, and relative standing on industry key ratios to assess comparative levels of resource efficiency. Indirect measures could well be developed from managerial or functional experts’ perceptions, either by questionnaire or through such techniques as the Delphi (Dalkey & Helmer, 1963).

The concepts I have developed here also have much to offer, both to the further development of resource-based theory and to the strategic application of real options theory. The concept of idiosyncratic reduction of uncertainty begins to move us as a field toward an unambiguous definition of when resources are likely to offer strategic value and when they are not. With respect to the real options literature, this article helps clarify the nature of options (as costs incurred to create underlying claims on future rents), as well as provides a coherent logic suggesting when those options should be exercised, when they should be held, and when they should be allowed to expire.

REFERENCES


Rita Gunther McGrath is an assistant professor in the Management of Organizations Division, Columbia Business School, and Research Director of the Snider Entrepreneurial Center, The Wharton School. She received her Ph.D. from The Wharton School, University of Pennsylvania. Her current research focus is on the strategic management of highly uncertain situations.