QUANTIFYING THE STRATEGIC OPTION VALUE OF TECHNOLOGY INVESTMENTS

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Abstract

We develop an integrated real options and industrial organization framework to quantify the strategic option value of technology investments. Strategic investments (e.g., R&D, capacity expansion or strategic acquisitions) are difficult to analyze based on standard approaches. Yet, it is these decisions that determine a firm's competitive success in a changing technological and competitive landscape. How much is a strategic option (e.g., Microsoft's growth opportunities) worth? How does one analyze strategic options in a dynamic, competitive environment? We describe basic principles for analyzing competitive strategies under uncertainty based on an integration of real options with game theory. We analyze multi-stage investment decisions facing a firm under uncertainty, both under a proprietary setting and when facing exogenous or endogenous competition (both in the last stage of commercialization as well as in the innovation or R&D stage). Competitive strategies may differ, e.g., depending on the type of investment (proprietary or shared) and the nature of competitive reactions (strategic substitutes or complements). The benefits of cooperation (via joint R&D ventures) vs. direct R&D competition (innovation races) are also discussed. Finally, we analyze multiperiod option games with endogenous volatility and discuss various other extensions.

1. INTRODUCTION

This article deals with a topic widely recognized as important in strategy and related disciplines, namely the quantification of the option value of investment strategies when the environment is uncertain and competition is dynamic. Recently, real options analysis has been credited with the ability to quantify the thus far elusive elements of operating flexibility and strategic behavior to capitalize on future opportunities (e.g., expand into new growth markets), retreat to limit losses from adverse market developments, or respond appropriately to competitive moves.[1]

The strategic management field itself has, in the past decade, seen the development of two main related but seemingly contradictory views. One main view recognizes that flexibility is valuable and that there is value in a wait-and-see or staging approach to decision making. As the competitive environment of most firms changes quite frequently, and sometimes drastically, flexibility in investment decisions should allow firms to adapt their future decisions to the changing environment, thereby optimizing their investments and value creation. The other main view argues that early commitment can be valuable because when a competitor commits itself in an irreversible way to a strategic investment, it can influence the strategic actions of its competitors in its favor. This creates the opportunity to realize strategic benefits (and enhance firm value).[2]

Both of these views are supported by a large body of research. The flexibility argument partly draws on the resource-based view of the firm and the core competence paradigm: a firm should invest in flexible resources or competencies which will give it a distinctive advantage to pursue a set of market opportunities (Penrose, 1959; Wernerfelt, 1984; Rumelt, 1984; Teece, 1984 and others). This position is also supported by the 'knowledge-based' and the 'dynamic capabilities' views of the firm (Teece, Pisano and Shuen, 1997). The view that an irreversible investment commitment can influence strategic behavior in desirable ways is firmly anchored in competitive analysis, industrial organization and game theory, which during the nineties saw an increasing adoption in the strategy field (Shapiro, 1989; Brandenburger and Nalebuff, 1995). Since both

[1] The option value of delaying investment was analyzed by McDonald and Siegel (1986). Dixit (1989) discusses a firm's entry and exit decisions under uncertainty, and Pindyck (1988) discusses the effect of flexibility in deferring irreversible investment and capacity choice. Grenadier (1996, 1997) analyzes exercise strategies for real estate development and for technological innovations. Competitive strategies using option and game-theory principles are discussed in Smit and Ankum (1993). The book by Tirole (1990) overviews strategic aspects of investment behavior in IO. The books by Dixit and Pindyck (1994) and Trigeorgis (1996) provide comprehensive treatments of real options investments under uncertainty.

[2] Real options became important for strategic management theory in the nineties. McGrath (1997) uses real options logic for initiating and amplifying the impact of technology investments. Bettis and Hitt (1995), and Bowman and Hurry (1993) suggest real options theory as an alternative valuation lens for technology and other strategic investments under uncertainty. Camerer (1991) discusses the opportunities and limitations of applying game theory in strategy research.

arguments have a theoretical justification, a key question is under what circumstances each position should inform strategy decision-making.

A key contribution of this paper is providing a coherent integration and synthesis of these two complementary perspectives, enabling management to *quantify* and resolve the flexibility vs. commitment tradeoff. To bring the flexibility and commitment perspectives together in a holistic framework that can support strategic investment decision-making, we propose adopting an expanded (or strategic) NPV criterion. This 'Expanded NPV', besides capturing the value of expected cash flows from preset operations and strategies, can also incorporate the new dimensions of flexibility and strategic commitment. To illustrate the use of option games for strategic management theory, we develop simple numerical models that integrate concepts from strategic management theory with real options and principles from game theory.[3] Finally, we discuss endogenous volatility and the nature of first-mover advantage via its impact on the value of growth options, and extensions involving technical R&D uncertainty, asymmetric or imperfect information, and learning effects.

The paper is organized as follows. Section 2 positions our framework in relation to existing strategic management approaches and presents a roadmap for analyzing competitive strategies. One-stage and two-stage strategic investment problems are discussed in sections 3, 4 and 5. Section 6 examines the issue of cooperation. Section 7 discusses endogenous volatility and other extensions in multiperiod option games. The last section provides a summary and concludes.

2. Position in Management Theory and a Road Map for Analyzing Competitive Strategies

Various paradigms in strategic management approach the underlying sources of value creation (and competitive advantage) by the firm from a different perspective. Table 1 summarizes the main frameworks and their perspective on strategy to position the emerging option games framework into the strategy literature. External approaches generally view value creation arising from external factors, such as economic profits in industries with competitive forces, market structure imperfections, synergies from product market combinations, or from strategic behavior.

[3] Models combining game theory and options in the economics and finance literature are typically based in continuous time and are developed from a theoretical perspective. Often, researchers assume that firms have the same costs or produce only one unit forever (if they are active in the market), and that the inverse demand curve is generic. Although interesting theoretical issues are investigated through these continuous-time models, the models are not readily applicable for practical valuation purposes or integration with the models in strategic management theory. In practice, firms are not generally homogeneous. The underlying stochastic variables are seldom likely to follow geometric Brownian motion, in particular for applications other than in natural resources. The firm must choose not only the optimal timing of an expansion but also the optimal capacity to install. It is much easier to handle asymmetries between competitors, path dependencies, and to define alternative stochastic processes when using a discrete-time approach. Such an approach is thus better suited for the integration of valuation and strategy.

A prominent external approach in the strategic management literature is that of strategic conflict, based on concepts from industrial organization and game theory. Game theory has been used in economics to formalize and model intuitive arguments about various types of firm behavior, for instance the role of commitment in R&D competition (Dasgupta and Stiglitz, 1980; Reinganum, 1985), patent races, capacity investment, signaling and reputation (Dixit, 1979, 1980; Spence, 1977, 1979), the type of competition (Fudenberg and Tirole, 1984, 1985),[4] and the tradeoff between commitment and flexibility (e.g., Appelbaum and Lim, 1985; Baldwin, 1987; Vives, 1989; Daughety and Reinganum, 1990; Green and Sadanand, 1991; Spencer and Brander, 1992; McGahan, 1993, Sadanand and Sadanand 1996, and others).[5] Since the 1980s there has also been a growing interest in the intuitive appeal of game theory concepts for strategic management theory applications, such as the role of commitment (Ghemawat and del Sol, 1998),[6] the trade-off between cooperation and conflict (Brandenburger and Nalebuff, 1995), and implications for joint ventures or research (Kogut, 1991; Chi, 2000).[7]

Game theory has occasionally been criticized that when it is used to rationalize observed firm behavior, the insights from the analysis are often self-evident. In industries with technological change, however, competitors can be dissimilar in many regards and the strategic position of the firm depends on the creation of new opportunities relative to competition. As we will see, coupled with real options thinking this approach can provide a more dynamic framework for strategic analysis and yield more powerful insights that depend on the evolution of the uncertain and changing environment. New and less obvious variables, such as volatility and correlation, may help explain more subtle differences in investment behavior and the sources of first- or second-mover advantage.

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[4] Fudenberg and Tirole (1984, 1985) examine the effect of strategic investment on second-stage value in a two-stage game when firms' actions (e.g., strategic variables such as prices or quantities) are strategic substitutes or complements.

[5] Baldwin (1987) discusses the tradeoff between preemption and flexibility for new product introductions. Appelbaum and Lim (1985) model an incumbent firm facing the trade-off between preemptive investment against the information effect of waiting. In Daughety and Reinganum (1990) firms can purchase information to help time their production. In Spencer and Brander (1992) a firm makes a trade-off between a Stackelberg leadership vs. a wait-and-see strategy that results in a simultaneous output game with its rival. They also deal with timing rivalry in the first stage and the timing of output decisions as a consequence of the degree of idiosyncratic uncertainty for each firm. In Green and Sadanand (1991) firms play a two-stage game: in stage 1, before uncertainty is resolved, both firms have an opportunity to commit output. In stage 2, after uncertainty is resolved, either firm chooses its output level. Vives (1989) shows that when investment encompasses flexibility to adjust to the environment (e.g., via a multi-purpose plant design), pre-commitment and flexibility are not necessarily substitutes. McGahan (1993) studies the tradeoff between commitment and flexibility in the case of the compact disk introduction. By building a large plant, Philips could preempt Sony and other potential competitors from building their own CD plants. She derives a threshold probability of market acceptance that would justify pursuing a wait-and-see strategy. In Kulatilka and Perotti (1998) the market structure is determined endogenously and is path dependent.

[6] Ghemawat and del Sol (1998) distinguish between firm-specific and usage-specific resources. Irreversible investments are firm-specific in that they involve significant cost to separate them from the firm. Usage specific-resources tend to restrict a firm's ability to change the way it is positioned in the product markets.

[7] Kogut (1991) analyses the effect of cooperation via joint ventures. Joint ventures are created as real options to expand in response to future technological and market developments. Like options, joint ventures help increase the upward potential while limiting downward losses. The results support the basic option asymmetry intuition: better-than-expected

An entirely different perspective is presented by the internally-focused approaches to firm value creation. In the resource-based view (Penrose, 1959; Wernerfelt, 1984; Rumelt, 1984; Teece, 1984), and in the "dynamic capabilities" perspective (Teece, Pisano and Shuen, 1997), the development and exploitation of scarce firm-specific resources and capabilities that give the firm a distinctive advantage to pursue a set of market opportunities is the fundamental determinant of value creation. The option games approach described herein is a further attempt at providing a linkage between the internal and external perspectives, enabling us to move from concepts to strategy valuation and implementation via the ability to quantify strategy development and adaptability.

Thus, a key differentiating contribution of the proposed option games approach to strategic management is that it enables quantification of qualitative strategic thinking. We share the view that firms follow an evolutionary path of competence and strategy development. From an options perspective, multi-stage investments are seen as links in a chain of interrelated projects or contingent strategic path segments, with each stage being an option on the next, developing competences, resources and capabilities, and generating new opportunities over time. A competence-building strategy is likely to be path- or history dependent. The chosen strategic path does not only define which investment alternatives are available to the firm today, but it also shapes its opportunities and exercise strategies in the future. Value derives not just from the expected excess profits generated from the existing asset base of the firm (depending on the degree of inimitability), but also from the firm's ability to adapt its strategy and transform itself.

Strategic growth options can be more effectively developed and exercised in line with the competences and capabilities that the firm has accumulated relative to its competitors. Early pre-emptive investment, patents, or a unique asset-accumulation path serve as isolating mechanisms enabling the firm to better appropriate future opportunities vis-à-vis competition. Asymmetries in asset base, investment exercise cost, firm-specific uncertainty, option maturity, or other option parameters can provide a rationale for one firm to act before another in an endogenous emergence of a leader-follower market structure. The value of the underlying asset-base cash flows, for example, is likely to be idiosyncratic as a firm may earn a higher premium because of differentiation, reputation or other effects. The exercise cost or expansion factor for exercising a strategic option may depend on the firm's historical path of capability development and on other parallel investments.[8] The value of flexibility to a firm may depend

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growth in the product market increases the likelihood of acquisition, while unexpected shortfalls in product shipments have no effect on the likelihood of dissolution.

[8] Evolutionary economics offers an alternative perspective on the innovative activity of firms. Dynamic capabilities that enable a firm to adapt fast can also be a source of sustainable competitive advantage. Different firms may have different capabilities, which evolve over time in a path (or history) dependent way. The benefits of dynamic capabilities are limited when learning is incremental and technology is proprietary and hard to codify. When one firm tries to improve its

not only on its own volatility but also on that of its competitor.

[insert Table 1 about here]

In the rest of the paper we describe a binomial option games approach that can help discipline the acceptable descriptive theory of strategic management via a more rigorous analytical valuation process. Our exposition is quite detailed in showing the different features and richness of the option-games framework. Table 2 helps provide a roadmap by showing how the analysis gets complicated in successive stages, and provides an overview of the structure of our paper. To introduce different aspects into the analysis one at a time, we start with simple one-stage investment decisions (options) under uncertainty (first when proprietary and then under exogenous or endogenous competition), and then extend the analysis to two-stage (compound) option games (again first with no competition, then with endogenous competition in the last stage only, and finally in both stages). We find it instructive to follow the following step-by-step thought experiment, starting with one-stage strategic investments:

1. Consider a high-tech company holding a one-year license (or patent) giving it a simple proprietary option to decide whether to invest in commercial production of a new product (a single-stage investment) this year or wait until next year when demand uncertainty will be clarified. What is the value of this license?
2. What is the impact on the value of the option to wait represented by the license when competitive entry can take part of total market value away from the incumbent? What if an early strategic investment by the incumbent can preempt competitive entry altogether (avoiding competitive value erosion), reverting back to capturing the full market value for itself?

Turning to two-stage strategic investments:

3. Stepping back in time to an earlier stage in the decision process of the high-tech company, should it make the R&D expenditure in the first place in order to acquire a proprietary option to proceed with the commercialization investment in the second stage (introduced in 1. above)? Similarly, how can we think about valuing an infrastructure investment, a strategic investment to gain a foothold in a new market, a strategic acquisition or other multi-stage growth options?
4. What is the impact on the firm's first-stage R&D strategy of facing (endogenous) competition in production (stage II) that can influence asymmetrically the equilibrium production outcome and its profit value? Can the optimal competitive R&D strategy be different depending on whether the

operations, its success is likely to be based on its own past activities and those of its rival. The value of dynamic capabilities may also depend on the stage in the development process. A "window of opportunity" will typically present itself in the early stage when the design is more fluent, manufacturing routines have not yet been developed and the firm has not yet committed capital. In the later stage a specialized design may emerge as network externalities or learning effects dominate. In this later, more rigid stage, the firm may not be able to adapt existing capabilities as effectively.

strategic R&D investment creates proprietary or shared benefits? How does it differ when competitive actions are strategic substitutes (where aggressive behavior by one firm may make its competitors less aggressive) than when they are strategic complements (where aggressive behavior by the firm leads its competitors to also behave aggressively)? In the latter case the total “pie” may get reduced if the competitors get into intensified rivalry or a price war. We suggest that the firm may be better off to make the strategic R&D investment in some cases (e.g., when there are proprietary benefits and firm's actions are strategic substitutes or shared benefits with firms' actions being strategic complements) but not in others.

5. Besides the firms competing in production in the second stage, what is the impact of them also competing in R&D (in the first stage) in a *sequential* investment timing game (e.g., an innovation race) whereby the first-mover can achieve a time-to-market advantage that may preempt its competitor and “win all”? But then what if both competitors end-up making a similar investment *simultaneously* such that one gets badly hurt or both are left worse off?
6. What are the benefits of instead cooperating in the first stage via a joint R&D venture, as many computer and other high-tech firms do today (while they may still compete in the last stage of commercial production)? Do the benefits of sharing the R&D costs and more fully appropriating jointly the option value of waiting under demand uncertainty outweigh any potential competitive advantage that a first-mover might achieve under a competing strategy?
7. How can endogenous volatility help create and sustain competitive advantage? What is the impact of delayed entry, technical R&D uncertainty, imperfect or asymmetric information, and of learning effects on the strategic decision?

[insert Table 2 about here]

We demonstrate the relevance of these models in practical examples to explain the mechanisms at work in the phenomena we observe in high-tech industries. Figure 1 shows examples of competitive strategies and relative market (price) performance over a recent two-year period in various high tech industries. Panel A shows Microsoft’s strategic moves and superior market performance over Netscape and other computer software rivals; panel B shows superior market performance by Intel and Sun Microsystems over IBM, Hewlett-Packard and other computer hardware rivals; panel C shows Texas Instruments and Philips’ performance relative to Sony, Time-Warner, Matsushita and other rivals in consumer electronics. We will relate our valuation framework to specific examples where some of these leading companies made intelligent strategic decisions and exercised important strategic options while some of their competitors failed.

[insert Figure 1 about here]

3. ONE-STAGE STRATEGIC INVESTMENTS

A. Simple Proprietary Options: A License by a High-tech Firm

In the case of a simple proprietary investment opportunity, when commercial prospects are uncertain, a firm may have an incentive to wait to invest until the market develops sufficiently, rather than investing immediately and killing its option to "wait and see" (e.g., McDonald and Siegel, 1986, Dixit and Pindyck, 1994). In 1990 Digital faced a timing decision as to when to commercialize its Alpha microprocessor chip and decided to wait in light of uncertainty in demand resulting from which product standard would prevail. Similarly in 1995 Sony had to decide when to commercialize the digital video disk (Multi-Media CD), developed in cooperation with Philips, under uncertainty over the future product standard and competitive moves.

To introduce the value of the flexibility to defer (a call option), consider the capital investment opportunity described in Figure 2.[9] A high-tech company has an exclusive opportunity (a license or patent) to build plant capacity for producing a new product that involves making an expenditure of I_0 = \$80m. Suppose that the (gross) value of expected future cash inflows from production equals 100, V_0 = 100, and may fluctuate in line with the random fluctuation in demand, say to $V^+ = 180$ or $V^- = 60$ (with equal probability, $q = 0.5$) by the end of the period (e.g., due to uncertainty over the product standard). In the absence of managerial flexibility, the traditional (static or passive) net present value, NPV = $V_0 - I_0$ = 100 - 80 = 20 (> 0), would justifiably lead to project acceptance.[10]

[insert Figure 2 about here]

What is really of interest in a world of uncertainty, competitive interaction, potential learning and adjustment,is not the value of the *immediate* investment per se, but rather the value of the *opportunity* to invest (i.e., the option to wait to invest for a period). The NPV rule, which attempts to account for a changing risk pattern through constant discount rates, does not properly capture the dynamics and active management of the investment under uncertainty.

Figure 3 shows that the *opportunity* to invest provided by the proprietary license or patent is more valuable than an *immediate* investment *commitment* since it allows management the *flexibility to defer* investment for a year and invest *only if* developments (e.g., demand or prices) are favorable (worth V^+ - I = 180 - 80 = 100 at the license's expiration at t = 1), or back out with limited loss (0) under

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[9] This example is similar to the one used by Trigeorgis and Mason (1987) and Trigeorgis (1996).

[10] Consequently, the project is expected to generate a t = 1 value of $E(V_1) = .5 \times 180 + .5 \times 60 = 120$; discounted at the opportunity cost of capital, assumed to be k = 20% (for the last stage of production), this results in a (gross) project present value of V_0 = 100. The firm would thus be willing to make an *immediate* investment outlay of I_0 = 80 in return for the higher present value of expected cash inflows, V_0 = 100.

unfavorable developments. The *opportunity to invest* provided by the license is thus analogous to a *call option* on the value of the developed (completed) project (V), with an "exercise price" equal to the required outlay, I = 80.

[insert Figure 3 about here]

The value of this investment opportunity (expanded NPV or NPV^*), seen as a call option, can be obtained from the end-of-period expected values (with expectations taken over risk-neutral or certainty-equivalent probabilities, here p = 0.4 and 1 - p = 0.6), discounted at the risk-free rate (here r = 0.08):[11] NPV^* or C = [.4 × (180 - 80) + .6 × 0]/1.08 = 37. Clearly, the value of the proprietary *opportunity* to invest provided by the license exceeds the passive NPV of an immediate investment commitment (37 > 20). In fact, such an investment opportunity (as provided by a license or patent) will have a positive value, even if immediate investment commitment would generate a negative NPV. *Since an early investment commitment sacrifices the value of the option to wait, this lost option value is an additional investment opportunity cost, justifying investment only if the value of cash inflows,* V*, actually exceeds the required outlay,* I, *by a significant positive premium.*

The above analysis is appropriate for *proprietary* investment opportunities. Many investment opportunities with high resource barriers of entry for competitors, such as a patent for developing a product having no close substitutes, or a unique know-how of a technological process or market conditions that competitors are unable to duplicate for at least some time, are examples of such proprietary real options. The (proprietary) option to wait is particularly valuable in resource extraction industries, farming, paper products, and real estate development due to the high uncertainties, long investment horizons and limited competitive erosion. However, in high-tech industries such as computers or consumer electronics, competitors can substantially influence a firm's opportunity value.

[11] The risk-neutral probabilities (that would prevail in a risk-neutral world where any asset is expected to yield the risk-free rate) can be obtained from:

$$p = \frac{(1+r)V - V^-}{V^+ - V^-} = \frac{(1.08)100 - 60}{180 - 60} = 0.4,$$

where V^+ and V^- are the end-of-period values. Note that if there are no options or other asymmetries (non-linearities), applying this risk-neutral probability measure (p) would give the same present value as traditional DCF valuation (e.g., see Trigeorgis and Mason, 1987):

$$V_0 = \frac{p \times V^+ + (1-p)V^-}{1+r} = \frac{0.4 \times 180 + 0.6 \times 60}{1.08} = \frac{q \times V^+ + (1-q)V^-}{1+k} = \frac{0.5 \times 180 + 0.5 \times 60}{1.20} = 100,$$

where q is the actual probability (of up demand moves), k is the risk-adjusted opportunity cost of capital, p is the risk-neutral probability and r is the risk-free rate.

B. Option Exercise under Endogenous Competitive Reactions

In the earlier example, management faced an *optimization problem* in that it could ignore any reciprocal effects of that decision on the competitor's actions. If, however, each firm's decisions depend on the other's moves, then a more involved *game-theoretic* treatment becomes necessary. Examples of such *shared real options* include the opportunity to introduce a new product impacted by introduction of close substitutes or to penetrate a new geographic market without barriers to competitive entry. The commercialization decision of Digital's Alpha chip was in fact greatly influenced by Intel's decisions regarding its Pentium processor; similarly, Philips and Sony's strategy to commercialize the Digital Video Disk was affected by competitive decisions by Toshiba and Time-Warner, and vice versa. Texas Instruments' entry into the digital TV with its digital light processing technology for high-quality big-screen television, developed over a decade for over $500m, faced competitive erosion with substitute products by Sony, Fujitsu, Sharp and others.

Investing earlier than one otherwise would to preempt anticipated competitive entry is a simple case of such *strategic option games*. More generally, instead of the optimization relying solely on option valuation techniques, the investment opportunity values at the end nodes in a binomial option tree would be replaced by the equilibrium outcomes of simultaneous competitive investment subgames.

Figure 4 illustrates such a game both in *extensive* form (tree to the left) and in *normal* form (value-payoff table to the right). Consider the resulting values either at the end of each tree branch or in the payoff table (firm A, firm B) in the following four investment-timing scenarios: (*i*) when both firms invest immediately (simultaneously) they share equally the total NPV (½ × 20), resulting in a (10, 10) value payoff for each firm; (*ii*)/(*iii*) when one firm (A or B) invests first while the other waits it preempts its competitor, appropriating the full NPV (20) for itself and resulting in a payoff of (20, 0) or (0, 20), respectively; and (*iv*) when both firms decide to wait they share equally the value of the defer option (½ × 37), resulting in a (18.5, 18.5) payoff.[12]

[insert Figure 4 about here]

In the above value-payoff structure of Figure 4 a *Nash-equilibrium* outcome is reached. Firm A's payoff from pursuing an immediate investment commitment strategy (lower row) exceeds its payoff from a wait-and-see strategy (upper row), regardless of which strategy firm B chooses (20 > 18.5 in left "wait" column, 10 > 0 in right "invest" column); that is, firm A has a *dominant strategy* to invest, regardless of the timing decision of its competitor. Firm B also has a dominant strategy to

[12] We model these games as games of complete information for simplicity. We comment on extensions with incomplete or asymmetric information in section 7.

invest, resulting in a Nash equilibrium (*) in the lower right cell, where both firms receive their second-worst payoff of (10, 10), an example of the well-known *prisoners' dilemma*. The paradox, of course, is that the equilibrium outcome (10, 10) is worse for both firms, compared with the situation when both choose to defer (18.5, 18.5). If the two firms could coordinate their investment strategy they could share the flexibility benefits of the wait-and-see option, potentially avoiding the inferior "panic equilibrium" where everybody rushes to invest prematurely.[13] We will return to examine how cooperation may improve the situation in section 6.

An important aspect in exercising options in a game context is the intrinsic value of the option or the value of immediate exercise (investment), V- I. The exercise cost (I) is likely to be idiosyncratic to each firm. Exercising the option to launch a new Windows-based package, for instance, is going to be less expensive for Microsoft than for another firm, by virtue of its dominance in desktops. The exercise price ratio may not be "half" of the total investment outlay for each player but instead an idiosyncratic value that is dependent on the position of the firm and the cost of the project. The value of the underlying cash flows, V, is also likely to be idiosyncratic, as firms may earn a higher premium because of reputation or other effects. The uncertainty each firm faces is likely to be idiosyncratic as well. Higher firm-specific uncertainty increases the value of a firm's growth options, increasing its incentive for waiting in the trade off between strategic commitment and flexibility.

When firms exercise their option sequentially (discussed in section 4 in more detail), first movership may provide differing advantages depending upon the quality and market power of the mover, the imitability (proprietary nature) of the incumbent's position, the time lag of the follower, learning, buyer's switching costs, and network externalities (see Lieberman and Montgomery, 1988). If the technology or position of the firm is more (less) difficult to protect, this erosion effect could be higher (lower). In high-tech industries, a firm may preempt competition and capture a significant share of the market by setting the product standard early on. Time to market may be an important source of advantage that may establish a sustainable strategic position for the organization. Intel preempted 80% of the microprocessor market with its Pentium microchip that became the product standard, forcing competitors like Digital to retreat from the market, even though Digital's Alpha chip was three to four times as powerful as the Pentium chip at a fraction of the cost. Network externalities can also influence the strategic game between firms in the choice of technologies. In the competition in video between VHS, Betamax and V2000 the early mover could develop a large install base and become the

[13] This observation has been analyzed extensively in the literature on investment under incomplete information, e.g., Hendricks and Kovenock (1989).

product standard. First mover advantage can be influenced by the reputation of a firm and buyer's switching costs, in cases where buyers develop brand-specific know-how that is not fully transferable if they switch (as in document processing). In some cases there may be second-mover advantages, typically present in two-stage games, where the follower can benefit from the pioneer's first-stage strategic investment (discussed in section 4).

Securing an early mover advantage may enable a firm to capture a larger share of the market. Whether the early mover advantage can be sustained depends on subtle ways of the industry context. Switching costs and network externalities may suppress competition in a later stage of the market (Klemperer, 1987). However, competition for market share by firms seeking to acquire an early mover advantage may be quite intense to be able to benefit from network externalities later on (Katz and Shapiro, 1986). We next turn to multi-stage strategic decisions.

4. TWO-STAGE (COMPOUND) OPTIONS: THE CASE OF PROPRIETARY R&D

The distinction between one-stage and two-stage option games or simple and compound options is important because most strategic options involve path dependent sequential investments. From a strategic management perspective, a sequential investment strategy can be seen as a staged commitment to create competences and accumulate resources that generate new investment opportunities. Many multi-stage investments appear to have a negative NPV when considered in isolation, although they may have substantial growth option value. In April 1997 Hewlett-Packard agreed to buy Verifone, the leading maker of credit card authorization devices, for $1.15 billion (although Verifone's 1996 earnings of just $39.3m gave a negative NPV) for its growth potential to dominate the emerging electronic commerce business. In the same month, Microsoft bought WebTV Networks, maker of set-top boxes that bring the Internet to TV sets, at a price of $425m, despite its losing over $30m in the past year alone. Again, this "negative NPV" acquisition can be justified for its growth option value as part of Microsoft's strategy of dominating the Internet.

What is the value of such a strategic acquisition or of an R&D venture that may result in uncertain future commercialization opportunities? Such investments often involve high initial costs and highly uncertain, contingent and remote cash inflows. Figure 5 illustrates a two-stage R&D project with an immediate, stage-I investment outlay of $I^I = 30$. Despite high costs and no expected cash inflows during the first stage, the investment may prove the new technology and enhance the company's market position if that market (or a spin-off product) develops. Investing now in the pioneer R&D venture derives strategic value from generating growth opportunities to invest in future commercial projects.

[insert Figure 5 about here]

The follow-on commercial project (stage II) has the same parameters as the proprietary option in the earlier example. Based on naive DCF analysis, the standard total net present value of this pioneer R&D venture is NPV = NPV (stage I) + NPV (stage II). Here, $NPV^I = - I^I = -30$ and $NPV^{II} = -26$.[14] Thus, if the firm were to commit to both stages right now, the total expected net project value would amount to $NPV = NPV^I + NPV^{II} = -30 + 26 = -4$ (< 0). Since commitment to this two-stage investment is expected to result in negative NPV, the calculation would lead to rejecting the R&D venture. However, top management may realize that it has an *option* (not a commitment) to invest in the second stage. *The negative NPV (cost) of first-stage R&D is the price that needs to be paid to acquire a growth option in the commercial project along the staged process.* Using options valuation, the value of the second-stage commercialization (growth) option is 37 (as in the earlier example).[15] Thus, the total strategic value (or expanded NPV) of the entire pioneer R&D venture is: $NPV^* = NPV^I + Option^{II} = -30 + 37 = +7$ (> 0), which makes the R&D investment worthwhile.

The more uncertain the technology or the more volatile the future market demand, the higher the option value will be.[16] This is so because the firm is asymmetrically positioned since it will invest in the follow-on commercial project (stage II) *only if* project value *at that time* turns out to exceed the required investment outlay of $I^{II} = 80$, but it has no obligation to proceed otherwise (truncating downside value to 0 rather than receiving 60 - 80 = -20, as might implicitly be factored into the expectation underlying a naïve application of NPV). It is important to recognize that different stages may have distinctly different risk characteristics: the first stage explores and creates options that can be exploited in the second stage. There is a distinction between uncertainties that investment can resolve via learning and those that cannot (e.g., see Dixit and Pindyck, 1993). The firms in the one-stage games of our

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[14] The follow-on commercial project (stage II) requires an outlay of $I^{II} = 80$ in year 1 and is expected to generate a value of subsequent cash inflows at that time of $E(V_1) = 120$ (= .5 × 180 + .5 × 60). This gives a time-0 second-stage value of $NPV^{II} = 100 - 74 = 26$ (after discounting $E(V_1) = 120$ at the opportunity cost of capital, k = 20%, and the known investment outlay of $I^{II} = 80$ at the risk-free rate, r = 8%).

[15] $Option^{II} = (0.4 \times \max(180 - 80, 0) + 0.6 \times 0)/1.08 = 37$ (rather than $NPV^{II} = 26$, as given by conventional DCF).

[16] In the NPV valuation high (market) risk results in a high required return by the capital markets and a low market value of the project considered for immediate investment. Real options introduce a new insight with respect to the effect of uncertainty on investment opportunity value that runs counter to this traditional thinking about the role of risk. High (total) risk has a positive influence on the value of real options. Standard finance theory, e.g., the Capital Asset Pricing Model (CAPM), assumes that investors are risk averse with respect to market risk in the sense that shareholders prefer a less disperse return distribution to a wide distribution of future returns with the same expected or mean value (Sharpe (1964), Lintner (1965)). Consequently, management might tend to think that higher market volatility should be priced less today in order to yield a premium that compensates for the market uncertainty. By contrast, the idiosyncratic (firm-specific or non systematic) uncertainty of stock returns does not require a premium since it can be avoided by portfolio diversification. In our context, this line of reasoning is still valid for the passive component of the expanded NPV. In the traditional valuation framework one can use the weighted average cost of capital (WACC) if the project has similar market risk characteristics as the average project or assets of the firm. However, the analysis of growth opportunities involves more than this framework may suggest. The value of growth derives from investments that the company could make in the future and is therefore more flexible in that management can change and adapt its decisions as various types of uncertainty get resolved over time.

framework face *market uncertainty* over operating cash flows that result primarily from uncertainties in demand or prices of factors of production. These uncertainties are largely exogenous to the firm.[17] This creates an incentive to delay exercise of simple options until more information is revealed that the project is clearly profitable. Of course, this depends on the context in that even attractive demand conditions may not generate favorable option values in cases where adoption rates are slow and commercialization costs are high (see McGrath, 1997). Two-stage games additionally include exploratory options involving firm-specific uncertainties (that may or may not be reduced by investment). These include technical, strategic, and organisational uncertainties.[18]

5. TWO-STAGE (COMPOUND) INVESTMENTS WITH ENDOGENOUS COMPETITION

As noted above, with an early strategic investment the firm may acquire options to capitalize on follow-on investment opportunities or may enhance its relative competitive position in a later stage of the market. In section 5A we introduce endogenous competition in the last stage (production) that may have a different impact depending on whether competitive actions are strategic substitutes or complements. In section 5B endogenous competition may take place both in the strategic investment (first) stage as well as in the production (second) stage.

A. Competition in Second Stage (Production): Strategic Substitutes vs. Complements

Sometimes competitive strategies are directed at hurting competitors' future profits so that they accept a smaller market share or even exit the industry, creating proprietary (monopoly) profit opportunities for an incumbent firm. On other occasions, for example if entry deterrence is not feasible or desirable (e.g., if it is too costly) or if competition is such that retaliation is likely and potentially very damaging, an incumbent may find it preferable to follow an accommodating strategy.

As noted in Fudenberg and Tirole (1984) and Tirole (1990), a key factor in determining an appropriate competitive strategy is whether a strategic investment makes the firm more "tough" (i.e., whether the firm can appropriate the resulting benefits and hurt its competitors), or "accommodating" (i.e., whether the resulting advantage will be shared with and benefit its rivals) in a later stage. A second factor, relating to how a firm expects its competitor to react to its actions, is whether the firms' actions are strategic substitutes or complements, i.e., whether the competitor’s optimal actions

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[17] The risks associated with the ultimate cash flows the firm realizes on completion of the project have a systematic component, while the purely technical risks are idiosyncratic. Berk, Green and Naik (2004) show that the systematic risk, and the required risk premium, of a venture are highest early in its life and decrease as it approaches completion.

[18] The uncertainty of “technical success” relates to the outcome of the R&D effort, e.g., in clinical testing in order to resolve side effects in the development of a new drug.

are similar or whether they are opposite to the (aggressive or accommodating) actions of the first-acting firm.

Capacity decisions and quantities are often regarded as strategic substitutes. A larger quantity produced by one firm (e.g., capturing a larger market share via economies of scale or a learning cost advantage) would result in a lower equilibrium (profit-maximizing) quantity by its competitor. Competitive actions under price competition are typically strategic complements, in that an action (e.g., price increase) invites a similar response by a profit-maximizing competitor. Here, a reduction in price by one firm would be matched by a profit-maximizing price cut by the competitor (and lower profit margins for both). Microchip prices, for instance, generally start out higher and then shrink rapidly due to intense price competition. Prices on the standard 16-megabyte chips have fallen 80% in 1996 alone. Similar price wars have often been disastrous in the food, tobacco and airline industries. In these circumstances, firms may be better off if one of the firms sets a higher price that competitors can follow, resulting in a larger pie for all.

Consider a two-stage game with endogenous competitive reactions in the second (production) stage among two otherwise comparable competitors. Similar to the earlier example of Figure 5, firm A (alone) can make a first-stage strategic investment of $I^I_A = 30$ (e.g., in R&D); this may be followed by a production investment of $I^{II} = 80$ by either competitor. When both firms decide to invest, the shared investment outlay made by each firm is half the total cost assumed in the proprietary R&D case (i.e., $I^{II}_A = ½ \times 80 = 40$).

Since a first-stage strategic investment in this context is made only by one of the competitors, it may influence asymmetrically their relative competitive position and market value outcomes (V_A,V_B) at time 1, depending on two main factors:

(a) The *type* of investment *(proprietary* vs. *shared)*: if the strategic investment (e.g., R&D or a marketing campaign) generates a competitive advantage with proprietary benefits (making the pioneer firm tough at the expense of competition), the pioneer captures most (here we assume $s = ⅔$) of the total market value ("pie") in the second stage. On the other hand, if the strategic investment benefits are diffused to the industry and also benefit competition (an accommodating stance), competitors share the total market value (here equally, or $s = ½$). The size of the pioneer's market share, s, depends on the context of the industry and the presence of first- or second-mover advantages (see, e.g., Lieberman and Montgomery, 1988). A pioneer firm may develop a new technology but fail to become the market leader if it cannot achieve sustainable competitive advantage in the second stage, e.g., when it lacks complementary assets needed to commercialize the product. On the other hand, an early mover may affect the pace of technological development or establish a product standard with network externalities that may increase its share of the pie, s.

(b) *The nature of competitive (re)actions (strategic substitutes vs. complements).*[19] In the case of strategic substitutes, firms have an incentive to make strategic investments (e.g., in R&D or marketing campaigns) to improve their competitive position and ability to appropriate future benefits for themselves. The total market value ("pie") is assumed to be given (a zero-sum game) so a firm with a proprietary competitive advantage would capture more share and value at the expense of competition (here s = 2⁄3 vs. 1⁄3). In the case the actions are strategic complements, on the other hand, an early strategic investment by a firm resulting in a proprietary advantage that would hurt its competitors may provoke intensified rivalry and a price war that in the end may damage the profit margins of both firms. In that case the total market value may decline (here we assume by a ¼). The total market "pie" may instead get enlarged (say by ¼) when a strategic investment is accommodating.[20] That would likely be the case when the investment benefits are shared. For example, an R&D innovation that is diffused to the industry or a marketing campaign focusing on the overall benefits of the industry's products (rather than the firm's specific brand) may increase overall demand and market value. An accommodating behavior does not necessarily presuppose cooperation or implicit collusion.

As illustrated in Figure 6, we can distinguish four different competitive investment strategies, depending on whether the resulting benefits of the strategic R&D investment are proprietary or shared and whether firms' actions are strategic complements or substitutes.

[insert Figure 6 about here]

1. Proprietary investment when firms' actions are strategic substitutes

R&D may generate a high strategic value if the technology can be kept proprietary (e.g., well protected by patents or by its install-base), creating a comparative advantage for the pioneer firm and forcing competitors to retreat. For example, suppose that R&D generates a proprietary advantage that

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[19] Strategic substitute vs. complement actions are typical for industries characterized by quantity vs. price competition, respectively. An interesting question is, when can one expect quantity or price competition? Cournot quantity competition more naturally arises in industries where firms set their investment and production decisions in advance and face higher costs for holding inventories. Firms first choose capacity (inflexible) and in a later stage choose production (quantity) to fill capacity. Here prices will adjust more quickly than quantities, with competitors expected to match any price change in order to meet their planned production, so price changes would not take business away from competitors. By contrast, Bertrand price competition pertains to markets where capacity is sufficiently flexible that firms can meet all demand at their chosen price. It is more applicable when firms' products are homogeneous or undifferentiated, believing that they can take business away from competitors if they cut prices. In some cases, Cournot and Bertrand competition may take place over different stages: competitors may choose capacities in the first stage, and then compete on price given the chosen capacities.

[20] In section 7 we model explicitly quantities and profits instead of capturing the end result simply by adjusting the total size

makes the pioneer firm stronger, hurting its competition in the second stage by capturing a larger share (2⁄3) of the market; if the competitor's actions are strategic substitutes the competitor will back down and accept a lower share (1⁄3). In panel A of Figure 7, the sub-game to the left concerns investment in follow-up production capacity (in stage II), and illustrates the competitive dynamics when demand and total project value are high ($V^+ = 180$). When both competitors invest in production capacity (low-right box), the value payoffs are (80, 20). Pioneer firm A generates a competitive advantage via its early proprietary strategic investment that allows it to capture ⅔ of total value by making a I^{II}_A = \$40m production capacity investment ($NPV_A^+ = \frac{2}{3} \times 180 - 40 = 80$). The competitor only captures $NPV_B^+ = 20$ ($= \frac{1}{3} \times 180 - 40$). Similarly, in the situation where both firms choose to wait, pioneer firm A appropriates a larger portion of the next-stage growth option value, \$81m, while firm B gets \$25m; this results in a (81, 25) value payoff (upper-left box).[21] In the off-diagonal boxes, each firm regards preempting the other and capturing the entire market value ($NPV^+ = 180 - 80 = \$100$m) as its most preferred outcome, (0, 100) or (100, 0). Under high demand, each firm has a dominant strategy to invest, regardless of its competitor's decision (for firm A, 100 > 81 and 80 > 0; for B, 100 > 25 and 20 > 0), even though both firms would be better off to wait. The Nash equilibrium (*) is the bottom-right, invest-invest outcome (80, 20).

Now consider the low-demand case ($V^- = 60$) to the right of Figure 7 panel A. Even if one of the firms were to invest alone, this would result in a negative value ($NPV^- = 60 - 80 = -\$20$m). If both firms wait, firm A would appropriate the full wait-and-see option value, resulting in payoffs (10, 0). In this wait-and-see scenario, firm A's dominant market power would enable it to preempt competitive entry in case next period's demand develops favorably to an intermediate level.[22] Both

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and sharing of the value "pie".

[21] If both firms wait, the competitive dynamics of the next-period subgames are as follows: firm A captures a larger market share ($\frac{2}{3}$V) at a very high level of demand ($V^{++} = 324$) and preempts the full value at lower, intermediate demand ($V^{+-} = V^{-+} = 108$), while both firms defer at very low levels of demand ($V^{--} = 36$).

At $V^+ = 180$ the option values therefore are:

$$OPTION_A^+ = \frac{0.4 \times (\frac{2}{3} \times 324 - 40) + 0.6 \times (1 \times 108 - 80)}{1.08} = 81; \quad OPTION_B^+ \approx \frac{0.4 \times (\frac{1}{3} \times 324 - 40) + 0.6 \times 0}{1.08} \approx 25$$

Similarly, at $V^- = 60$ the option values are:

$$OPTION_A^- \approx \frac{0.4 \times (1 \times 108 - 80) + 0.6 \times (0)}{1.08} \approx 10; \quad OPTION_B^- \approx \frac{0.4 \times 0 + 0.6 \times 0}{1.08} \approx 0$$

[22] At an intermediate level of demand ($V^{-+} = 108$) total market value is sufficiently low that the competitor's value would be negative ($NPV_B = \frac{1}{3} \times 108 - 40 = -4$) if they both invest, while firm A's NPV would still be positive ($NPV_A = \frac{2}{3} \times 108 - 40 = 32$). Consequently, firm A has a dominant strategy to invest while firm B defers, resulting in a Nash equilibrium where firm A preempts with a (108 - 80 = 28, 0) payoff.

firms have a dominant strategy to defer under low demand, with firm A capturing the full growth option value.

[insert Figure 7 about here]

To summarize, during the second stage (as of t = 1), both firms will invest in case of high demand, and defer otherwise. In case of high demand ($V^+ = 180$) firm A captures a larger share in Nash equilibrium ($NPV_A^+ = 80$) due to its proprietary R&D advantage, while in case of low demand ($V^- = 60$) its dominant position again enables it to preempt the full growth option value ($Option_A^- = 10$). Using binomial option valuation, the current value of firm A's investment opportunity one period earlier (at t = 0) is given by: $Option^{II} = (p \times NPV_A^+ + (1 - p) \times Option_A^-)/(1 + r) = (0.4 \times 80 + 0.6 \times 10)/1.08 = 35$. Thus, the total strategic or expanded NPV of firm A's proprietary R&D investment under second-stage endogenous competition is: $NPV_A^* = NPV^I + Option^{II} = -30 + 35 = +5$ (> 0). Thus, the pioneer should make the strategic R&D investment.

The above analysis confirms that an early R&D investment may be warranted if it makes the firm tough and hurts its competition in a later stage; when the competitor's actions are strategic substitutes, it may follow a share-retreat strategy with the pioneer expanding its market share as demand grows. If demand turns out sufficiently low that the competitor's profit value turns negative, the pioneer can preempt competitive entry and earn monopoly profits.[23]

2. Proprietary benefits when competitors' actions are strategic complements

Consider now the case that the competitor would reciprocate rather than retreat. Unlike the previous case of competition that creates incentives to take an offensive stance to increase one's ability to preempt a larger share of the market, here a tough stance (via a proprietary strategic investment) when competitors' actions are strategic complements may instead result in intensified rivalry, a decline in total market value and reduced profit margins.

In May 1997 Microsoft announced an all-out attack into the lucrative heavy-duty corporate computing market, traditionally a mainframe task performed by IBM, Sun Microsystems and Oracle. This was a high-risk strategy for Microsoft: if successful, it could have a sweeping impact on business computing, just as its Windows software had on PC's. But its competition, already having made heavy investments, did not seem ready to retreat; instead it was poised to *reciprocate* and fight to the end: "Every major corporation needs its Vietnam, and this will be Microsoft's", responded an IBM executive (*NY Times*, 5/19/97).

[23] This proposition is well understood in the IO literature (see, for instance, von Stackelberg, 1934). Here, the tradeoff between option value and commitment is made more explicit.

Such intense price competition had already been taking place in networking products. As of January 1997 Intel moved aggressively into this market, forcing competitors to reduce their prices; in April 1997 Intel announced it would invest even more as this was a “very high priority” on its list of growth areas. Novell Inc., maker of computer networking software, got hurt as a result, announcing in May 1997 cutting 18% of its work force “in response to competitive pressures in the market for networking products” (*NY Times*, 5/29/97).

How would our analysis of a proprietary technological innovation be different if actions were instead strategic complements? Suppose that generating a proprietary competitive advantage via a strategic investment will again enable firm A to capture ⅔ of stage-II total value, but now it will invite a tough reaction by a competitor such that total market value will decline (e.g., due to price competition) by ¼ (to ¾ V). This game is illustrated in Figure 7 panel B. The decline in total market value as a result of intensified rivalry offsets the advantage of capturing a larger share due to the proprietary advantage of the strategic investment for firm A. The share for firm A is now $\frac{2}{3} \times (\frac{3}{4} V) = \frac{1}{2} V$, while firm B receives $\frac{1}{3} \times (\frac{3}{4} V) = \frac{1}{4} V$. Consider the subgame under high demand ($V^+ = 180$) at the left of Figure 7 panel B. When both firms decide to invest, firm A receives an NPV of $\frac{1}{2} \times 180 - 40 = 50$ and firm B receives $\frac{1}{4} \times 180 - 40 = 5$, whereas if they both choose to wait firm A retains a growth option value of 61 and firm B of 15.[24] However, both firms again have a dominant strategy to invest under high demand (50, 5). The competitor is worse off, but the damage is not enough to preempt its entry under high demand (5). The values under low demand ($V^- = 60$) are similar, resulting in a similar wait-wait equilibrium outcome (10, 0).Thus $NPV_A^* = -30 + (0.4 \times 50 + 0.6 \times 10)/1.08 = -30 + 24 = -6$ (< 0). *To avoid such a potentially damaging rivalry, a firm may therefore be better off deciding not to invest if its investment will provoke an all-out war.*[25] In the 1980’s Philips, who collaborated with Sony in the development of the VCR standard, learned the hard way losing out to Matsushita and switching over to the standard that prevailed.

3. Shared benefits when competitors' actions are strategic complements

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[24] The competitive dynamics of the second-period subgames are similar to those in footnote 16: firm A captures a larger market share under intense rivalry ($\frac{2}{3} \times \frac{3}{4} V$) at a very high level of demand ($V^{++} = 324$) and preempts at lower, intermediate demand ($V^{+-} = V^{-+} = 108$), while they both defer at very low levels of demand ($V^{--} = 36$). For example, at $V^+ = 180$ the option values equal:

$$OPTION_A = \frac{0.4 \times (\frac{1}{2} \times 324 - 40) + 0.6 \times (1 \times 108 - 80)}{1.08} = 61; \quad OPTION_B \approx \frac{0.4 \times (\frac{1}{4} \times 324 - 40) + 0.6 \times (0)}{1.08} \approx 15$$

[25] This result, already known in IO (e.g., see Fudenberg and Tirole, 1984), is again confirmed from a combined real options – game theory perspective. Although not necessary, proprietary technology is more likely to strengthen the pioneer and weaken the competitor, provoking a retaliatory response.

A decade later the same players followed a different strategy, choosing to adopt a common, industry-wide standard for the high-density CD. These players seemed to realize that when firm actions are strategic complements it may be better to follow an accommodating strategy that would enhance the total value for the industry. Another example of an investment with shared benefits is Mobil placing a goodwill ad in the *NY Times* educating the public about the benefits of oil refining for society in general (rather than its specific products).

In the example shown in Figure 8 panel A, the strategic investment brings shared benefits for the competitor, who is ready to reciprocate. The higher prices attained result in higher profit margins for both and an enlarged total market value by ¼ (to $^5/_4$ V), shared equally by both firms. Under high demand, both firms will invest to receive $\frac{1}{2}\times\left(\frac{5}{4}\times 180\right)-40=73$, resulting in a symmetric Nash equilibrium outcome of (73, 73); under low demand, both firms will choose to wait, obtaining (10, 10).[26] Investment in the strategic project with shared benefits is thus justified in this case: The total strategic value of the pioneer R&D venture for firm A is: $NPV_A^* = -30 + (0.4 \times 73 + 0.6 \times 10)/1.08 = -30 + 33 = +3\ (> 0)$.

Shared R&D can bring a strategic advantage when firms whose actions are strategic complements can share a larger market value. This may be due to option value benefits (e.g., appropriating the option value of waiting under demand uncertainty), or due to sharing strategic benefits such as avoiding price rivalry or a war of attrition among competing standards.[27]

[insert Figure 8 about here]

4. Shared investment when firms' actions are strategic substitutes

In a different competitive landscape, sharing technological innovation may result in a vulnerable strategic position for the pioneer if a competitor can take advantage of its accommodating stance and the generated shared knowledge. In May 1997, one week after Intel announced its next-generation microprocessor, the Pentium II, Digital sued Intel claiming remarkable similarities with its Alpha chip; Digital had revealed the Alpha design to Intel during their failed negotiations on licensing Alpha technology for Intel's next-generation chip in 1990-91. In an independent suit in 1997, Fujitsu agreed to pay compensation to IBM in a decade-old suit for allegedly copying IBM products.

[26] The growth option values for the subgames under high demand ($V^+ = 180$) and low demand ($V^- = 60$) for both firms A and B are as follows:

$$\text{OPTION}^+ = \frac{0.4\times(\frac{1}{2}\times\frac{5}{4}\times 324-40)+0.6\times\left(\frac{1}{2}\times\frac{5}{4}\times 108-40\right)}{1.08} = 75;\quad \text{OPTION}^- = \frac{0.4\times(\frac{1}{2}\times\frac{5}{4}\times 108-40)+0.6\times(0)}{1.08} = 10$$

[27] There are many other dimensions that can affect the value of the firm's options, including the possibility of collaboration or collusion.

In our valuation example where the benefits of the strategic investment are shared, a competitor whose actions are strategic substitutes can take advantage of the pioneer's accommodating position and capture half of total market value (assumed given). Consider the symmetric subgame under high demand ($V^+ = 180$) at the left of Figure 7 panel B: when both firms decide to invest they both receive an NPV of $\frac{1}{2} \times 180 - 40 = 50$, whereas if they both choose to wait they each receive a growth option value of 53.[28] However, both firms have a dominant strategy to invest early regardless of the other's action, resulting in the symmetric Nash outcome of (50, 50). Under low demand, the firms would be better off to wait, obtaining (5, 5). This results in a negative total strategic value for the pioneer's R&D venture: $NPV_A^* = -30 + (0.4 \times 50 + 0.6 \times 5)/1.08 = -30 + 21 = -9$ (< 0).

There is less competitive advantage for a pioneer firm to single-handedly make a costly strategic investment when the resulting benefits would be shared with competition without reciprocity. A competitor whose actions are strategic substitutes can take advantage of the pioneer's accommodating position and capture part of the shared benefits of the pioneer's strategic investment, without sharing in the cost. The pioneer may in some cases be better off to avoid subsidizing the creation of such shared opportunities for competition if it believes they may eventually be used against it.

We turn next to two-stage games with endogenous competitive reactions in the first (R&D) stage.

B. Competition in Innovation Investment: Time-to-Market Races and Strategic Alliances

An additional dimension is introduced when either of the two firms can make independent, strategic R&D investments in the first stage (as well as compete in the second, production stage). In this case firms may feel competitive pressure to rush into an innovation or patent race.[29]

Suppose that technological investment by both firms now increases total market value (say by ¼), while the other parameters remain the same as in the proprietary investment case when firms' actions are *strategic substitutes*. We consider first the situation where the firms invest sequentially in R&D with

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[28] The values in this case are:

$$\text{OPTION}_A^+ = \frac{0.4 \times (\frac{1}{2} \times 324 - 40) + 0.6 \times \left(\frac{1}{2} \times 108 - 40\right)}{1.08} = 53; \quad \text{OPTION}_A^- = \frac{0.4 \times (\frac{1}{2} \times 108 - 40) + 0.6 \times (0)}{1.08} = 5$$

[29] Grossman and Shapiro (1986, 1987) and Reinganum (1985) discuss R&D in a competitive context, while Dasgupta and Stiglitz (1980) and Fudenberg, Gilbert, Stiglitz and Tirole (1993) discuss patent races. In a Poisson-type patent race it is often assumed that a firm's probability of making a discovery and obtaining a patent depends on its R&D expenditures. These models show that uncertain R&D may be more valuable. As in real options theory, this result is based on an inherent value asymmetry. In a "winner-takes-all" game, the firm benefits from the high upside potential, while on the downside it does not matter how far behind it finishes in the patent race because the patent will be worthless anyway. The option games approach is particularly appropriate for R&D valuation, also taking account of the "winner-takes-all" nature of the patent system. Weeds (2002) derives optimal investment strategies for two firms that compete for a patent that may help explain strategic delay in patent races, shedding light on the role of first vs. second movers. Lambrecht (2000) and Miltersen and Schwartz (2003) consider innovation with uncertainty over completion and time delays, which can explain phenomena like faster exit ("reverse hysteresis") and delayed commercialization ("sleeping" patents).

the first-mover obtaining a competitive time-to-market advantage (e.g., a patent). We then examine the situation where both may invest *simultaneously* in R&D with equal market power.[30]

[insert Figure 9 about here]

Figure 9, panel A shows the case of ***sequential*** R&D. There are four scenarios:

(i) If the two firms invest in R&D in sequence, with firm A investing before firm B, the first-mover obtains a competitive time-to-market advantage that allows it to capture ⅔ of the total (expanded) market value in each demand state. The follower's payoff equals $\frac{1}{3}\times(\frac{5}{4}\times 180)-40=35$ in case of high demand, and -15 in low demand – preferring instead to wait (0). At low demand, the technology leader (firm A) also prefers to wait a period (preempting competitive entry in case demand later increases) appropriating the growth option value of 20,[31] while capturing a greater market share in case of high demand ($\frac{2}{3}\times\frac{5}{4}\times 180-40=110$). The total strategic value for the follower therefore equals $NPV_B^* = NPV^I + Option^{II}$ (Shared) = -30 + (0.4 × 35 + 0.6 × 0)/1.08 = -17 (< 0); for the leader, NPV_A^* = -30 + (0.4 × 110 + 0.6 × 20)/1.08 = 22 (> 0). Being the first mover confers a significant strategic advantage in this case.

(*ii/ iii*) In case an early innovator's (either firm A or B) R&D investment preempts the competitor's entry and establishes the industry standard, the winner's value would equal $145\ (=\frac{5}{4}\times 180-80)$ in case of high demand, or a growth option value of 20 under low demand. Consequently, the total strategic value of winning the product standard equals NPV^* = -30 + (0.4 × 145 + 0.6 × 20)/1.08 = 35, resulting in (35, 0) or (0, 35) payoffs, respectively.

(iv) In the scenario where both firms decide to defer investment in R&D they would share the growth option value symmetrically. At a high level of next-period demand they will both invest simultaneously (NPV^+ = -30 + 73 = 43), while at a low level both will choose to abandon (NPV^- = 0), resulting in a payoff of (16, 16) for each firm.[32]

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30 Timing games are well understood in the IO literature, particularly that on endogenous timing of investment and preemption (e.g., Anderson and Engers, 1994, or Holder and Riis, 1994). This section illustrates the timing issues properly incorporating the option value of waiting under uncertainty.

31 $$\text{OPTION}_A^- = \frac{0.4\times(1\times\frac{5}{4}\times 108-80)+0.6\times 0}{1.08}=20$$

32 At t = 2 both firms invest at high demand (V^{++} = 324) and wait (abandon) at low demand. At t = 1,

$$NPV^+ = \frac{0.4\times(\frac{1}{2}\times\frac{5}{4}\times 324-40)+0.6\times\left(\frac{1}{2}\times\frac{5}{4}\times 108-40\right)}{1.08}-30=73-30=43$$

$$NPV^- = \frac{0.4\times(\frac{1}{2}\times\frac{5}{4}\times 108-40)+0.6\times\max\left(\frac{1}{2}\times\frac{5}{4}\times 36-40,0\right)}{1.08}-30=10-30=-20<0\quad\text{(choose 0)}$$

Thus, growth option value (at t = 0): $\frac{0.4\times(43)+0.6\times 0}{1.08}=16$.

Since firm A can make its R&D investment decision before firm B, to decide which timing strategy to follow it must recognize how its decision will influence its competitor's behavior. If firm A pursues a wait-and-see approach, while firm B rushes to make an R&D investment (receiving 35 rather than 16 from waiting), firm A's payoff will be 0. However, if firm A pursues an early technological investment commitment strategy, firm B will choose to wait (receiving 0 rather than -17 if it also invests with a delay), in which case A's payoff will be 35. Thus, firm A would invest immediately to signal a credible commitment to the market and deter competition. The equilibrium outcome in this case is (35, 0).

In reality, the value of an option is likely to be idiosyncratic to each firm, due to differences in firm-specific uncertainty, exercise costs, option expiration, even discount rates and the cost of capital. Hence the different, firm-specific value of the growth options introduces an asymmetry where a firm with lower firm- specific uncertainty, exercise cost or maturity may exercise its options early and invest first, while another may rationally choose to wait.

In the literature on patent races, success of R&D depends on how long it takes to achieve usable outcomes (the hazard rate of R&D success), who wins the race (which depends on the number of participants), and the degree to which a winner can appropriate the resulting advantage (Dasgupta and Stiglitz, 1980). These factors can to some extent be influenced by investment: the hazard rate of success, and hence the chance of winning the race, may be increased by increasing R&D intensity.

In practice we often see firms rushing into innovation races and forming strategic partnerships to acquire a first-mover or time-to-market advantage. Consider for example the race in memory chip development: In February 1997 Hitachi, Mitsubishi Electric and Texas Instruments announced they would jointly develop a one-gigabyte DRAM. NEC, which has been co-operating loosely with ATT-spin-off Lucent Technologies and Samsung, announced in June 1997 that it had developed a 4-Gb DRAM, the largest-capacity memory chip ever developed, putting NEC in the lead in the intensely-competitive memory chip technology race.

Under competitive pressure to be the first (e.g., in a patent race) competitors may rush to make parallel innovation investments ***simultaneously***, with one or both sides potentially getting hurt. Novell got hurt due to competition in networking products, Apple lost its lead as a user-friendly computer with the development of Microsoft's Windows, while in the 1980's Philips got hurt from losing the race against Matsushita over the VCR standard.

Let us revisit the numerical example of the investment timing game above, but with the twist that the competing firms (or alliances) can invest *simultaneously* in R&D, as shown in Figure 9, panel B. This involves larger total expenditures in the first stage ($I_A + I_B = 60$), while the two firms share total market value symmetrically: $72.5\ (= \frac{1}{2} \times \frac{5}{4} \times 180 - 40)$ under high demand or 10 under low demand. The total strategic value for each firm now is: NPV^{I} + $Option^{II}$ (Shared) = -30 + (0.4 × 72.5 + 0.6 × 10)/1.08 = 2.

In many emerging, high growth industries, the possibility of each firm pursuing independent R&D activities to capture the product standard may trigger a simultaneous similar investment by competitors that, like in a prisoners' dilemma, can make both firms worse off [(2, 2), compared to a scenario of waiting (16, 16)]. Without a first-mover advantage, this simultaneous game provides a lower value-payoff for firm A (2) than in the above sequential game (35).[33]

The strategic moves by Microsoft to gain an advantage in its continuing battle with Netscape over who will be the Internet standard bearer could be seen in this light. The purchase of WebTV might help Microsoft outflank its rivals, including Oracle and Sun Microsystems as well as Netscape. A reciprocating reaction, however, came from Oracle and Netscape. In May 1997 Oracle gave a boost to its strategy of developing a network computer as an alternative to the PC (dominated by Microsoft Windows software and Intel chips), announcing a majority investment in Navio Communications, established by Netscape to develop Internet software for consumer electronics; Navio recently also made deals with Hewlett-Packard, Sun Microsystems and others threatened by Microsoft.

6. COOPERATION IN THE FIRST STAGE: JOINT R&D VENTURES

Given that independent R&D investments by each competitor may lead to a race that may damage one or both sides, an interesting question is whether two firms (or alliances) should pursue independent, competing R&D activities or instead cooperate in the first stage via a joint research venture, competing only in the second stage of commercial production and sales.

Figure 10 illustrates the valuation of first-stage cooperation via a joint research venture. Cooperation via joint R&D has the following implications for competitive R&D strategies:

(i) Joint R&D may have a beneficial impact on value (NPV) by providing comparable R&D benefits while sharing the R&D costs among the cooperating firms (15 vs. 30, if equally shared among two firms). The value of investing immediately in the joint R&D venture for each firm is -15 + 32 = +17 (> 0).[34] A joint R&D venture not only provides a mechanism to share the scale economies in R&D,

[33] The situation triggering simultaneous investment by competition has been extensively studied in the investment cascade literature (e.g., see Hendricks and Kovenock, 1989).

[34] This equals 2 (from the simultaneous investment of Figure 9, panel B) plus half the saved expenditures (15). Alternatively, if both invest simultaneously (cooperatively),

$$NPV_A = NPV_B = \frac{0.4 \times (\frac{1}{2} \times \frac{5}{4} \times 180 - 40) + 0.6 \times 10}{1.08} - 15 = 32 - 15 = 17$$

but may sometimes enhance them as the parties may bring different complementary skills, thereby lowering the total investment costs.

(ii) It may enable the two firms to more fully appropriate the flexibility value from waiting under demand uncertainty. If both firms above choose to wait to invest and appropriate the option value of waiting (16) plus save (make only) half of the R&D costs (15) in case of high demand next period, the option value in the joint venture will be worth 16 + (0.4 × 15 + 0.6 × 0) /1.08 = 22.[35] With R&D cooperation there is no sacrifice of flexibility value from an attempt to preempt the market as under direct R&D competition.

It is known that risk reduction can be achieved through organizational mechanisms, but organizations may also benefit from uncertainty. Joint ventures may serve as platforms for possible future development, where uncertainty might have a possible impact on the value of the venture. Chi (2000) provides an interesting discussion on joint venture options. Kogut (1991) provides empirical evidence that joint ventures can be motivated by the option to expand in new markets and technologies where the option to expand is more valuable. The evidence also shows that strategic factors, such as market concentration, influence the creation of joint ventures. In Kogut's (1991) study it is hypothesized that the timing of the acquisition is triggered by a product market signal, indicating an increase in the venture's valuation. The results show that unexpected increases in the value of the venture and the degree of market concentration significantly affect the likelihood of an acquisition.

(iii) Of course to achieve these benefits the firm must give up the possibility to gain a first-mover advantage via preempting its competitor (the R&D investment in the preemptive sequential game is worth 35 while the joint R&D option is worth 22). However, at the same time joint R&D ventures may have a beneficial impact on the strategic effect in high-tech industries, and the strong position of the alliance may result in a first stage "technology shake-out" of inferior and dominated technology.

Besides the above benefits, alliances and joint ventures may suffer from several drawbacks. An alliance often forces parties to exchange considerable information and independent firms may lose control over proprietary information. In addition, the governance structure of the alliance may not provide a formal mechanism for decision making. Finally, agency costs can arise, because the benefits of the alliance are split among the two or more firms, giving rise to free-rider problems.[36]

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[35] The value if invest at t = 1 under high demand equals 73 - 15 = 58 (see footnote 27 for calculation of option value = 73 at V^+), so that:

$$\text{Option value of waiting (at } t = 0\text{):} \quad \frac{0.4 \times (58) + 0.6 \times 0}{1.08} = 22$$

[36] Garlappi (2002) models R&D in an interactive competitive setting and analyses the impact of competition on the risk premia of ownership claims to R&D ventures engaged in a multiple-stage patent race. As in Berk, Green and Naik (2004), successfully completing an R&D stage reduces the implicit leverage, and the risk premia decrease as a

Most of the new product introductions in electronics have been based on product standardization agreements in R&D. In 1995 the alliance of Philips and Sony (that developed the Multi-Media CD) came to agreement with the alliance of Toshiba and Matsushita (that developed the Super-Density Disk) to set a common industry standard for the new-generation high-density CD (the Digital Video Disk); the computer industry encouraged the two sides to coordinate, avoiding the major waste of capital and confusion that would have resulted from the launching of multiple systems (as happened a decade earlier when the two sides competed against each other, with the Philips alliance losing out). Other examples involve joint R&D ventures, especially among US and Japanese firms: Toshiba and IBM shared the $1 billion cost of developing a 64mb and 256mb memory-chip facility outside Nagoya using IBM's know-how in chemical mechanical polishing (the technology was to be transferred back to an IBM plant in Virginia in 1997). Canon and Hewlett-Packard share laser engine printer technology, even though they compete fiercely with their end products around the world. Kodak and arch rival Fuji have for years collaborated on joint research on a new advanced photo system.[37]

The above examples were based on stylized bimatrix competition. Among other simplifications, option parameters (e.g., exercise price, firm-specific volatility or option maturity) were assumed given. Of course there are many complexities in reality that present more richness than our above stylized models, including option parameters that can be influenced by competitive behavior. The timing of entry and the nature of competitive advantage, for example, may better be captured by endogenizing some of these option parameters. For instance, it may be possible to some extent to influence a competitor's option value by investments that increase entry barriers (increasing the option exercise price for competition). The exercise cost or exercise capacity of a firm may also depend on what other orgnizational assets and resources the firm has. The value of the underlying cash flows (V) is also likely to be idiosyncratic, as firms may earn a premium because of reputation or other effects. Further, beyond the technical uncertainty of the innovative (R&D) process, organizational and strategic uncertainties may also be subject to influence.[38] In the next section we present various extensions of the above analysis, including a model where volatilities in the second stage may be determined

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consequence of technical progress, while they increase when a rival pulls ahead in the race due to the threat of preemption. Thus, under R&D competition the dispersion of value increases while faster completion due to competition reduces it.

[37] Recently we also witness a cooperation trend in production and services among many leading Japanese and US firms: IBM and Toshiba jointly manufacturing liquid-crystal display panels; GE supplying components to Toyota, while Toyota helps distribute GM's Cavalier through its dealership network in Japan; Mitsubishi and Dupont launching a joint polyethylene manufacturing venture; Sumitomo and Exxon cooperating in oil and gas development in China, etc.

[38] Strategic uncertainty relates to competitive interaction, first- or second-mover advantages, and market entry and pre-emption. There may also be uncertainty concerning the intensity of competition among incumbent producers, or about new entrants, depending on the contestability of the market.

endogenously, explaining how first-mover advantage may arise in the first stage and get reinforced.

7. MULTI-PERIOD OPTION-GAMES WITH ENDOGENOUS VOLATILITY AND VARIOUS EXTENSIONS

The above stylistic two-stage investment games can be extended in a dynamic, multi-period setting to also capture the effects of delayed entry (e.g., Stackelberg leader-follower), endogenous volatility, technical uncertainty of the R&D process, asymmetric information, learning effects, and other extensions. A particular contribution is that future industry structure can be explained more realistically with such dynamic investment option games. Different market structure games and corresponding equilibrium values are determined *at the end* of the last (commercialization) stage. These are described in Figure 11 and Table 3.[39] The terminal equilibrium values are a non-linear function of the evolution of exogenous market demand (θ). At high levels of demand both firms may decide to invest in productive capacity (I) in the same period *(simultaneously)*, and a Cournot Nash equilibrium is reached when each firm reacts optimally to the other firm's expected quantity (as expressed by its reaction function, R), i.e., $Q^*_A = R_A(Q^*_B)$ and $Q^*_B = R_B(Q^*_A)$.[40] At intermediate levels of demand a sequential Stackelberg leader/follower game can result. Given that the follower will observe the leader's prior output, the Stackelberg leader will choose that output on the follower's reaction function, $R_B(Q_A)$, that will maximize its own profit value, i.e., max $V_A(Q_A, R_B(Q_A))$ over Q_A. At low levels of demand both defer.

This more realistic basic option game can be further extended in several directions. Most important is the situation where volatility is varying endogenously, depending on the evolutionary path of demand and the investment behavior of the competitors. Furthermore, rather than assuming the special case of sure R&D success under complete (symmetric) information, the analysis can be extended within a more general model that allows incorporating technical R&D uncertainty, incomplete information, learning cost effects and other real-life complications.

A. Endogenous Volatility: Creating and Sustaining First-Mover Advantage

Empirical observations suggest that asset return volatility is often not constant but in many cases it may be inversely related to the value of the underlying asset. The volatility of the underlying asset values

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[39] The symbols C, S, M, A, D at the bottom of Figure 11 refer to the different market structure games described herein (and summarized in Table 3). The state payoff values at the end of the second stage are the outcomes of different market structure games depending on the state of demand (θ), each firm's actions (invest, do not invest/defer) and their timing (simultaneous or lagged, at t = 1 or 2).

[40] A reaction function assigns to every output level of one firm the value-maximizing output of the other (in quantity competition).

along the equilibrium path to reach the terminal equilibrium values also depends on the interaction and evolution of market demand, the relative strategic position of the rivals, and the outcome of the competitive subgames in the two stages. We subsequently simulate numerical results based on such more realistic modeling assumptions.

Table 4 shows the (dynamic) market structure outcomes, equilibrium values, and volatilities for firms A and B, when firm A has a comparative cost advantage as a result of making a proprietary first-stage strategic R&D investment. The first two columns show the dynamics of the market structure with demand fluctuations. For example, for very low levels of demand an early investor may not find it profitable to invest in the follow-up commercial project and both will defer. For intermediate levels of demand, an early investor may deter (or delay) potential entrants and capture monopoly or Stackelberg leader profits. For high levels of demand, investing early brings higher value resulting in a Cournot Nash equilibrium for both firms. Figure 12, panel A, shows how the total value in the commercialization stage for firm A (Expanded-NPV or NPV^*_A as of t = 1) varies with market demand θ. The firms' decision to invest or defer depends on two critical (threshold) market demand parameters, θ^*_{INVEST} and θ^*_{DEFER}, separating the range of demand states into three demand zones. If market demand θ exceeds θ^*_{INVEST} (= 14), each firm (as a follower) has a dominant strategy to invest, resulting in a Cournot Nash equilibrium market structure. If θ is below θ^*_{DEFER} (= 9), at the intersection of the invest/defer and defer/defer curves, both firms have a strictly dominant strategy to defer. In the intermediate zone (above θ^*_{DEFER}), an early entrant (pioneer) would earn Stackelberg leader or monopolist profits. Here a strategic R&D investment improves the pioneer's relative strategic position via lowering future production costs, expanding market share and (potentially) preempting competitive entry. The equilibrium market price P* (third column of Table 4) and the expanded net present values NPV^*_A and NPV^*_B (fourth and fifth columns) generally increase with demand, but discontinuities may arise when the market structure changes (e.g., from Monopoly or Stackelberg leader to the Cournot Nash equilibrium). These discontinuities are also manifested in how volatility varies with market demand across the different demand zones (Figure 12, panel B).

Interestingly, although primary uncertainty originates from market demand fluctuations, volatility becomes endogenized via the behavioral uncertainty of strategic interactions among the players along the equilibrium path. The volatility of the underlying investment project is likely to be different for each firm, depending on the evolution of market demand θ, the relative advantage position of the firm, and the firm's and its competitor's entry/defer decisions and the resulting market structure. This effect can be observed from Figure 12, panel B, and the last two columns of Table 4, showing the underlying volatility conditional on the market structure outcome (in the first period of commercialization). Figure 12, panel B, confirms that volatility declines as market demand (and equilibrium value) rises. The volatilities for firm A and B change along the uncertain future trajectories of demand. It can also be seen that volatility, being conditional on the market structure, exhibits a discontinuity at the point when firms make their entry decisions. For instance, the volatility for firm B jumps from 53% to 45% when the market structure changes from Stackelberg follower to Cournot Nash (around $\theta^{*}_{INVEST} = 14$). Finally, the volatility is idiosyncratic for each firm and depends on its relative strategic position. The firm with earlier strategic investment and comparative cost advantage (pioneer firm A) ends up with lower volatility ($\sigma^*_A < \sigma^*_B$) and higher equilibrium profit value. Endogenous volatility affects the option values and this effect is taken into account ex ante (before investing), influencing investment timing decisions. Initial heterogeneity of firms (e.g., with a pioneer firm attaining lower costs or earlier time to market) may thus influence the order of entry in a sequential investment whereby a resulting lower volatility for the pioneer may further sustain the first-mover advantage. As long as it is optimal for the follower to wait, the pioneer may enjoy excess profits, enhancing value and further sustaining its first-mover advantage effect.

B. Various Other Extensions

Table 5 summarizes parameter values and numerical results by extending the model in various other directions, such as incorporating technical uncertainty that the R&D efforts will succeed or not, effects of asymmetric or imperfect information, and learning cost effects. The implications of these model extensions are briefly discussed next.

Technical uncertainty in the R&D process. Technical uncertainty in the outcome of the R&D process generally enhances the flexibility value of waiting and reduces the strategic preemption and commitment value of R&D (compared to the situation of certain proprietary R&D). That is, with the same expected cost reduction (mean-preserving spread), *sure R&D success leads to higher preemption value (discontinuity) due to strategic interactions in the second stage.* Asymmetries in the competitive position of the firms can further emerge due to the path-dependent nature of the R&D development process. McGrath (1997) also suggests that learning in R&D is a path-dependent process that may involve a lock-in for a certain technology. Productive routines in technology can not always be considered as “lucky accidents” where idiosyncratic technical uncertainty resolves over time through investment. Often this technological discovery process involves learning via which those within the firm can gain a greater understanding of how to influence action-outcome relationships, resulting in different firms having different uncertainty profiles.

Asymmetric/imperfect information. In a more general framework there may be incomplete information if firms are not aware of each other’s R&D success or cannot observe the innovations of competitors and their precise costs. Although an innovator would know (ex post) whether its own innovation efforts succeeded or not, its rival may not know this with certainty and may have to design a strategy based on its expectation of the rival’s behavior and costs. In multi-period games, a firm’s behavior as a successful (or failing) innovator may involve revealing some of its private information or even signaling its innovation success as a commitment to a certain technology or market for preemptive purposes. Under incomplete information it is likely that the value of flexibility and strategic reaction becomes less important due to “averaging out” of these opposite effects in firm B’s response (from using firm A’s expected rather than actual costs).[41]

Learning effects. Besides reducing future production costs via making a strategic R&D investment in an innovative new production process, firms can alternatively achieve cost reduction via learning by investing earlier in (cumulative) production. Learning and experience curve effects are

[41] Under asymmetric (imperfect) information in quantity competition, firm A may have an incentive to provide (partial or misleading) information over the success of its R&D efforts. If its R&D efforts were successful, firm A would have an incentive to communicate/signal this to firm B to induce it to set a lower quantity and soften second-stage competition. By contrast, firm A has an incentive not to inform B in case its R&D efforts are failing. At first glance, firm A thus appears to have an incentive to always tell its competitor that its R&D effort is successful, whether it actually succeeds or not. Of course this is not credible as firm B knows this and would not be fooled. If firm A always informs in case of R&D success but keeps silent in case of failure, firm B will infer that no information (silence) implies that A’s R&D actually failed and will increase quantity competition accordingly in a repeated game.

particularly significant if intricate or complex tasks must be performed, as in consumer electronics or the design and production of software. The "learning curve" encapsulates a cost advantage deriving from accumulated experience and know-how. The rate of learning, i.e., how fast the operational cost declines when cumulative production increases, is likely to be firm-specific as different organizations and processes embody different levels of experience and know-how. There is thus an important trade-off between waiting or the value of flexibility to adapt to change and early investment to take advantage of cumulative cost experience and learning benefits (e.g., see Majd and Pindyck, 1987).[42] As higher learning favors early investment, learning is likely to erode flexibility value (while it increases the direct NPV value due to cost savings). The learning process is likely to be path-dependent, i.e., when demand develops idiosyncratically, firms following different paths can result in a different build-up of experience.[43] These different experience paths can trigger different strategic decisions that may influence sustainable competitive advantage differentially. Therefore, investment timing and growth option value may depend not only on the *level* of demand but also on the *historical paths* of demand for the firm (and its competitors).

When, besides learning, we additionally consider strategic R&D commitment, the total value of the R&D strategy does not only depend on the pioneer's learning benefits; its strategic preemptive value is also dependent on the cumulative production and learning rate of the rival. The R&D pioneer may lose preemption value if the rival can more fully exploit a learning cost advantage. Preemption with a strategic investment can thus be more valuable if it can prevent the competitor from taking advantage of own learning experience cost effects. In this context, technical R&D uncertainty brings about interactive side effects, i.e., only if the pioneer's R&D succeeds would there be a preemptive effect.

8. Summary, Implications and Conclusions

This article presented a stylized option games framework for analyzing various competitive strategies, allowing us to quantify the value of flexibility and strategic commitment and identify those strategic factors that affect total shareholder value creation.[44] An important element of this

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[42] With learning, the marginal cost of firm *i* (*i* = A, B) is assumed to decline exponentially with cumulative production $\Sigma Q_{it}\left(= Q_{it} + \Sigma Q_{it-1}\right)$ at a learning rate γ, converging to a floor level c_i^F according to $c_i\left(Q_{it}\right) \equiv c_i^F + c_i^L e^{-\gamma \Sigma Q_{it}}$.

[43] For instance, early high growth may trigger a large investment and learning that preempts competitive expansion and thereby changes the relative strategic position of the firms. Seizing a first-mover advantage is important in this context as the market leader can accumulate more experience and gain a cost advantage. As costs continue to decline, it would become increasingly more difficult for imitators to catch up. This experience development process may be quite different when demand increases incrementally to the same level.

[44] The above option-game analysis naturally inherits some of the problems of game theory in general, e.g., it prescribes

framework is the extent to which the option-game valuation is consistent with and reinforces the intuitive strategic logic underlying established but complementary strategic management theories. The flexibility argument draws on the resource-based and dynamic capabilities views, where an investment strategy in flexible resources or competencies can be seen as a first link in a chain of future options development. From the perspective of the commitment view, these options should be exercised early if they could beneficially influence the strategic behavior of competitors.

The quantitative apparatus afforded by an integration of real options and game theory can support and complement strategic management theory in an interactive way and yield powerful insights in uncertain and dynamic environments. The combined real options and game theory framework can help guide managerial judgment in deciding whether, when, and under what conditions it would be appropriate to make or alter an investment. It can also help management decide whether to go at it alone, or whether to cooperate with other players. We summarize some of our key results below and then explore some of the implications for management theory.

In the analysis of one-stage investment options under uncertainty, we discussed the trade-off between the flexibility/learning value from waiting under demand uncertainty against competitive erosion and preemptive commitment effects. In analyzing two-stage or compound option games (e.g., R&D, capacity expansion, or strategic acquisitions), we recognized that an early commitment may not only result in future commercialization or growth opportunities but it may also influence the competitor's future behavior in desirable or potentially damaging ways. A pioneer, for example, may use a first-stage R&D investment to gain a strategic advantage via lower future operating costs or an expanded market share when competitive reactions are strategic substitutes. In other cases, however, an early investment commitment may create a strategic disadvantage if it reduces the firm's ability to respond toward aggressive competitors who can exploit shared benefits resulting from the strategic investment, or if it provokes a retaliating response and intense rivalry that may badly damage both competitors when competitive actions are strategic complements. The impact (sign) of the strategic commitment effect may differ, depending on the nature of competitive reactions (strategic complements or substitutes) and on whether the benefits of R&D are proprietary or shared.

We then examined competition in technological innovation (e.g., R&D) among two competitors during the first stage, e.g., when each firm strives to acquire the product standard. Tempted by the potentially high payoffs of acquiring the dominant product standard or being left with nothing (a "winner-takes-all" situation with a call-option asymmetry), firms may get trapped in a patent or

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what the players should do when they all behave rationally. It is part of a conceptual framework for sensible managerial guidance, but it does not cover all the angles for successful strategic behavior (Camerer, 1991).

innovation race in an effort to preempt each other. Such competitive pressure may result in a prisoners' dilemma with an inferior "panic" equilibrium outcome where everybody rushes into R&D prematurely, sacrificing the flexibility benefits of a wait-and-see strategy. A joint research venture enabling the firms to cooperate in R&D during the first stage may be a way to avoid this prisoners' dilemma. Joint research, besides sharing (reducing) investment costs, may enable the cooperating firms to more fully appropriate the flexibility (option) value from a wait-and-see approach under technological or demand uncertainty, avoiding the competitive pressures of an innovation race to preempt the market.

Besides confirming and quantifying many of the insights from different established complementary strategy views, it should be noted that several new variables, such as volatility, correlation, investment exercise cost timing and staging, may help explain more subtle differences in investment behavior, the sources of first- or second-mover advantage, or the intensity and type of competition and its impact on growth option value. Interesting implications can be drawn, for example, concerning the nature of first-mover advantage, depending upon (endogenous) volatility, the quality and market power of the mover, the imitability (proprietary nature) of the incumbent's position, the time lag of the follower, switching costs, learning effects, and network externalities. In many high-tech industry contexts innovation leadership is based on timing advantage. A firm or an alliance that can bring out new products faster to the market can enjoy a significant advantage. In addition, the quality of its products and its organizational resources and capabilities are often idiosyncratic to the firm and can also be a source of comparative advantage in the development and exercise of the firms' strategic options.

The factors driving the value of each firm's growth options may generally be idiosyncratic to each firm, generating significant inter-firm asymmetries that can help explain differences in exercise and timing behavior (e.g., first mover or follower entry). A firm with lower firm-specific uncertainty, investment exercise cost or option maturity (e.g., anticipating earlier competitive entry) may exercise its options early while another may rationally choose to wait. The exercise cost or exercise capacity of a firm may also depend on what other organizational assets and resources the firm already has put in place (McGrath, 1997). In some cases, a firm may influence a competitor's options, e.g., by investments that increase entry barriers (increasing the exercise cost for competitor's options). Beyond technical R&D uncertainty and market demand or price uncertainties, there may also be substantial strategic and organizational uncertainty. Strategic uncertainty relates to issues of competitive interaction, first- or second-mover advantages, and market entry. There may also be uncertainty concerning the intensity or type of competition between incumbents, or about new entrants, depending on the contestability of the market.

From an options perspective, multi-stage investments are seen as links in a chain of interrelated projects or strategic path segments, developing flexible resources and capabilities over time to capitalize on future opportunities, as part of a broader management strategy. Different firms have (developed) different capabilities, which evolve over time in a path-dependent way. For example, firm A's history of competence or capability development may differ from firm B´s. Consequently, a firm’s growth option value at a point in time depends not only on the level and volatility of demand and other key value drivers, but also on the historical path development of these value drivers for the firm in relation to its competitors.

Of course there are many complexities in reality that present more richness than our stylized models. Our models, presented in a simple way for clarity, were intended to serve as benchmarks for a more rigorous strategic analysis. Our analysis was simplified in several ways. For example, we ignored the context when rivals are more than two. The analysis would provide similar results with a limited number of players but as the number of players increases, the reaction of players and equilibrium results become less predictable. More than two competitors may also limit the strategic effect from preemption, and the jumps in value would be smaller. The effect of more competitors might introduce more volatility (more smaller changes) in firm value. As the number of firms increases, the market structure would tend to change from oligopoly to perfect competition, where the individual strategic impact of competitors becomes negligible, but might still be captured via an exogenous dividend-like effect.

The above simple option-game examples provide valuable insights for certain strategic contexts by endogenising strategic interactions. It is important, however, to recognize that the appearance of entirely new kinds of competitors or entirely new technologies can significantly modify the game at play. In the new uncertain competitive landscape that high tech and other industries are facing today, it becomes essential for firms to be more flexible in their investment programs, allowing management to change the amount, rate, timing or scale of investment in response to new, unexpected developments and competitive moves. However, this flexibility must be balanced against the strategic value of early commitment. We suggest that strategic management theory may benefit from integration with real options and game-theoretic principles within a comprehensive, consistent framework for analyzing strategic investments and quantifying the tradeoff between strategic adaptability and commitment in a dynamic competitive environment. This approach provides a richer framework that can help management better understand the strategic mechanisms at work and firm behavior observed in high tech industries. Applied to corporate strategy generally, it may be the best attempt so far to subject strategic management intuition to the discipline of a more rigorous analytical valuation process.

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TABLE 1 External and Internal Views of the Firm and Approaches to Strategy

	PARADIGM	REPRESENTATIVE AUTHORS	UNIT OF ANALYSIS	FOCAL CONCERN
EXTERNAL	1. Industry and Competitive Analysis	Porter (1980)	Industry (firms/ products)	Structural conditions and competitor positioning
	2. Strategic conflict/ Game Theory	Shapiro (1989) Brandenburger and Nalebuff (1995)	Firms/ products	Strategic interactions
INTERNAL	3. Resource-Based View	Rumelt (1984) Wernerfelt (1984) Teece (1980,1982)	Internal capabilities/ resources	Asset Accumulation
	4. Dynamic Capabilities	Prahalad and Hamel (1990) Dierickx and Cool (1989) Teece, Pisano, Shuen (1997)	Processes/ positions/ Paths	Asset accumulation, replicability
LINKAGE	5. Real Options and Games	McGahan (1993) Smit and Ankum (1993) Kulatilaka and Perotti (1998) Smit (2001) Bowman and Hurry (1993) McGrath (1997)	Above under uncertainty	Adjusting decisions in a dynamic and competitive environment

TABLE 2. Successive stages of analysis, types of option games and related literature, problem description, implications and examples/applications

Type of option game	Analyzed by	Problem Description	Implications	Examples/Applications
Section 3A. One-stage games with no competition (proprietary option).	McDonald and Siegel (1986), Brennan and Schwartz (1985).	Investment *opportunities* can be viewed as simple proprietary options to invest. For example high-tech company holding a one-year license (or a patent expiring in a year) giving it an option to decide whether to invest in commercial production of a new product this year or wait until next year when demand uncertainty will be clarified.	Incentive to delay investment under uncertainty (as found in resource extraction industries).	In 1990 Digital faced a timing decision as to when to commercialize its Alpha microprocessor chip and decided to wait in light of uncertainty in demand resulting from which product standard would prevail. Similarly, in 1995 Sony had to decide when to commercialize the digital videodisk (Multi-Media CD), developed in cooperation with Philips, under uncertainty over the future product standard and competitive moves.
Section 3B. One-stage games with exogenous competitive impact (shared options).	Dixit (1979, 1980) Spence (1977, 1979), Kester (1984), Baldwin (1987), Trigeorgis (1988), Gemawat and del Sol (1998).	Shared investment opportunities where anticipated competitive loss can be viewed analogous to the impact of dividends on a call option. Examples include the opportunity to introduce a new product impacted by introduction of close substitutes or to penetrate a new geographic market without barriers to competitive entry.	Incumbent faces a tradeoff between the value of flexibility to wait and the competitive value erosion due to postponement.	The introduction of the multimedia compact disk developed by Sony (and Philips) in 1995 faced exogenous competitive erosion from companies like Toshiba, Time-Warner and Matsushita (with the Super-Density Disk). Similarly, Texas Instruments' entry into digital TV with its digital light processing technology for high-quality big-screen television, developed over a decade for over $500m, faced anticipated competitive erosion with substitute products by Sony, Fujitsu and Sharp.
Section 3C. One-stage games with endogenous competitive reactions.	McGahan (1993), Smit and Ankum (1993).	A *game-theoretic* treatment becomes necessary. Have incentives to invest earlier than one otherwise would to preempt anticipated competitive entry (*strategic games against competition).*	Competitors face a timing game where investment may preempt competitors from exercising their shared rights.	The commercialization decision of Digital's Alpha chip was greatly influenced by Intel's decisions regarding its Pentium processor; similarly, Philips and Sony's strategy to commercialize the Digital Video Disk was affected by competitive decisions by Toshiba and Time-Warner, and visa versa.
Section 4. Two-stage options with no competition.	McGrath (1997), Bettis and Hitt (1995), Bowman and Hurry (1993).	Investments in growth options, for example the analysis of R&D expenditures in order to acquire a proprietary option to proceed with the commercialization investment in the second stage.	Negative NPV of the first stage can be justified for its growth option value.	In April 1997 Hewlett-Packard agreed to buy Verifone, the leading maker of credit card authorization devices, for $1.15 billion (although Verifone's 1996 earnings of just $39.3m gave a negative NPV) for its growth potential to dominate the emerging electronic commerce business. In the same month, Microsoft bought WebTV Networks, maker of set-top boxes that bring the Internet to TV sets, at a price of $425m, despite its losing over $30m

				in the past year alone.
Section 5A. Two-stage games with endogenous competition in stage II.	Dasgupta and Stiglitz (1980), Appelbaum and Lim (1985), Daughety and Reinganum (1990), Spencer and Brander (1992), Kulatilka and Perotti (1998).	First-stage R&D strategy, facing (endogenous) competition in production (stage II) that can influence asymmetrically the equilibrium production outcome and the incumbent's profit value.	Competitive strategy based on the *type* of investment *(proprietary* vs. *shared) and the nature* of competitive *reaction*	Cooperation in (second-stage) production and services among many leading Japanese and US firms: IBM and Toshiba jointly manufacturing liquid-crystal display panels; GE supplying components to Toyota, while Toyota helps distribute GM's Cavalier through its dealership network in Japan; Mitsubishi and Dupont launching a joint polyethylene manufacturing venture; Sumitomo and Exxon cooperating in oil and gas development in China, etc.
Section 5B. Two-stage games with endogenous competition in both stages.	Appelbaum and Lim (1985), Spencer and Brander (1992).	Endogenous competition in the first stage affects the value in the second stage.	Trade-off between cooperation and competition	Race in memory chip development: In February 1997 Hitachi, Mitsubishi Electric and Texas Instruments announced they would jointly develop a one-gigabyte DRAM. NEC, which has been co-operating loosely with ATT-spin-off Lucent Technologies and Samsung, announced in June 1997 that it had developed a 4-Gb DRAM, the largest-capacity memory chip ever developed, putting NEC in the lead in the intensely-competitive memory chip technology race.
Competition vs. cooperation in stage I (joint R&D ventures).	Kogut (1991).	Cooperation competition in the first stage affects the value in the second stage.	Evolution of cooperation in technology intensive industries.	In 1995 the alliance of Philips and Sony (that developed the Multi-Media CD) came to agreement with the alliance of Toshiba and Matsushita (that developed the Super-Density Disk) to set a common industry standard for the new-generation high-density CD (the Digital Video Disk). Other examples involve joint R&D ventures, especially among US and Japanese firms: Toshiba and IBM shared the $1 billion cost of developing a 64mb and 256mb memory-chip facility outside Nagoya using IBM's know-how in chemical mechanical polishing (the technology was to be transferred back to an IBM plant in Virginia in 1997).

TABLE 3. Equilibrium Quantities, Profits and State Project Values for Various Market Structures under Contrarian Quantity Competition in the Second Stage

Second-stage Game

Action[1] (A, B)	**Market Structure N/M/S/A/D**	**Equilibrium Quantity Q^*_i**	**Equil. Profit[2] π^*_i**	**State Project Value[3] NPV_i**	**Demand State θ_t**
(DI, DI) (II, II)	Nash Cournot (N)	$\frac{(\theta_t - c_i)(2+q_j)-(\theta_t - c_j)}{(2+q_i)(2+q_j)-1}$	$\frac{(\theta_t - 2c_i + c_j)^2}{9}$	$\frac{(\theta_t - 2c_i + c_j)^2}{9k} - I$	$\geq 3\sqrt{kI} + 2c_i - c_j$
(DI, DD)	Monopolist (M)	$\frac{\theta_t - c_i}{2+q_i}(Q_j = 0)$	$\frac{(\theta_t - c_i)^2}{4}(\pi_j \leq 0)$	$\frac{(\theta_t - c_i)^2}{4k} - I$	$< 3\sqrt{kI} + 2c_j - c_i$
(II,DI)	Stackelberg Leader (S^L)/ Monopolist (M)	$\frac{(\theta_t - c_i)(2+q_j)-(\theta_t - c_j)}{(2+q_i)(2+q_j)-2}$	$\frac{(\theta_i - 2c_i + c_j)^2}{8}$	$\frac{(\theta_t - 2c_i + c_j)^2}{8k}$ - I'	$\geq 4\sqrt{kI} + 2c_j - c_i$ ($< 4\sqrt{kI} + 2c_j - c_i$)
(DI,II)	Stackelberg Follower (S^F)	$\frac{(\theta_t - c_j)(2+q_i)-(\theta_t - c_i)}{(2+q_i)(2+q_j)}$	$\frac{(\theta_t - 2c_j + c_i)^2}{16}$	$\frac{(\theta_t - 2c_j + c_i)^2}{16k}$ - I	$\geq 4\sqrt{kI} + 2c_j - c_i$
(DD,DD)	Abandon (A)	0	0	0	

Period 1

(I,I)	Nash Cournot	$\frac{(\theta_t - c_i)(2+q_i)-(\theta_t - c_j)}{(2+q_i)(2+q_i)-1}$	$\frac{(\theta_t - 2c_i + c_j)^2}{9}$	$\frac{\theta_t - 2c_i + c_j)^2}{9k} - I$	
(I, D)	Monopolist (M) Stackelberg Leader (S^L)	$\frac{\theta_t - c_i}{2+q_i}$	$\pi_m = \frac{(\theta_t - c_i)^2}{4}$	$\frac{pV^c{}_u + (1-p)V^c{}_d}{1+r} - I + \frac{\pi_m}{1+k}$	
(D,D) (D,I)	Defer (D)	0	0	$\frac{pNPV^*{}_u + (1-p)NPV^*{}_d}{1+r}$	

1 During period 1, (A, B) means that firm A took action A while competitor firm B took action B. During the entire second stage, (AA', BB') means that firm A took action A in period A in period A' in period 2, while firm B took action B in period 1 and B' in period 2.
2 Calculated from $\pi_i = P_iQ_i - C(Q_i)$, assuming for simplicity $q_i = q_j = q = 0$.
3 Determined in the last stage from $NPV_i = \max(\pi_i/k - I,0)$, where I is required outlay and k the risk-adjusted discount rate. In the first period, it may be determined from future expanded (strategic) net present values (NVP*) in the up and down states using backward binomial risk-neutral valuation.

TABLE 4. Second-stage Dynamic Market Structures, Values (NPV*), Dynamic Volatility, and Demand (θ) for Proprietary R&D Investment

θ	Market structure (dynamic)	*Proprietary strategic investment* P*	Expanded Value NPV^*_A	NPV^*_B	Volatility (dynamic) σ^*_A	σ^*_B
6.75	Both Defer	-	0	0	42%	80%
8.10	Both Defer	-	18	0	41%	67%
9.72	Monop./Stackelberg	5.36	46	0	40%	59%
11.67	Monop./Stackelberg	6.33	119	0	40%	53%
14.00	Cournot Nash	5.67	68	3	36%	45%
16.80	Cournot Nash	6.60	141	63	36%	44%

Parameter values
Investment: K_A =100, $I_A = I_B$ = 100; interest rates: r = 0.10, k = 0.13; demand uncertainty: u = 1.20, d = 0.83; no technical R&D uncertainty: η_A = 100%; no learning: γ = 0%. Proprietary R&D costs: c_A =1, c_B = 2;

TABLE 5 Overview of the Breakdown of Value Components for the Strategic R&D Investment of Firm A in Different Cases

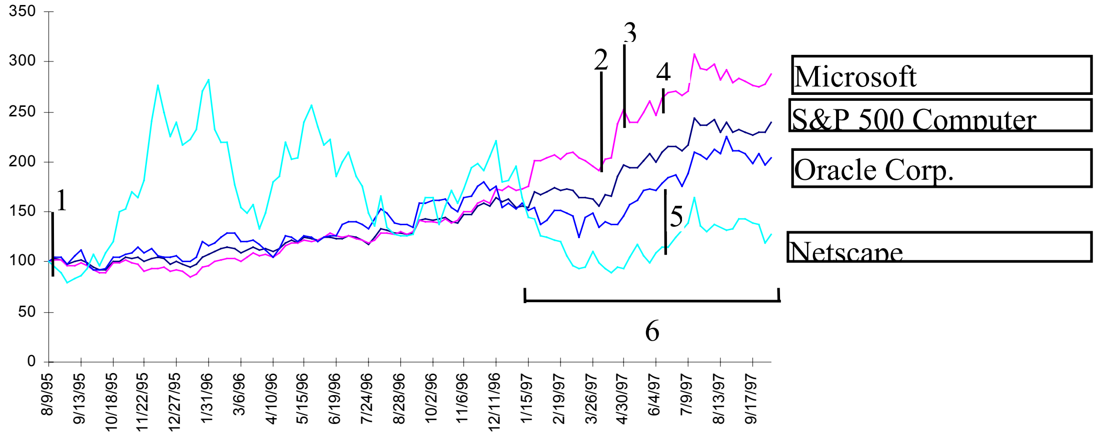
	Basic game (sections 2 and 3)			***Uncertain R&D*** (η =50%) (section 4)			***Learning*** (γ =10%) (section 5)		***Cooperation (vs. competition)*** (section 6)	
	(1) base case (no R&D)	(2) proprie-tary R&D (K = 100)	(3) shared R&D	(4) complete info. (propr.)	(5) imperfect info.	(6) signal-ing	(7) base case	(8) propr. uncertain R&D	(9) R&D compet. (K = 100)	(10) R&D cooper. (K = 50)
(1) direct		186	186	93	93	93	111	37	93	83
(2) strat. reaction		82	-72	41	31	44	-45	15	-16	-32
(3) strat. preempt.		45	0	22	34	28	0	44	11	0
(4) Net commit. value (1+2+3-K)		213	14	56	58	65	66	-4	-12	6
(5) flex. value	23	0	0	12	9	6	0	0	17	25
(6) base-case NPV	37	37	37	37	37	37	37	103	37	37
TOTAL EXP. NPV (4+5+6)	60	250	51	105	104	108	103	99	42	68

Parameter values: investment: K_A =100, $I_A = I_B = 100$; interest rates: r = 0.10, k = 0.13; demand uncertainty: u = 1.25, d = 0.8; no technical R&D uncertainty: $\eta_A = 100\%$; technical R&D uncertainty: $\eta_A = 50\%$; no learning: $\gamma = 0\%$, learning: $\gamma = 10\%$.

A. Base-case costs: $c_A = 5, c_B = 5$;
B. Proprietary R&D costs: $c_A = 0, c_B = 5$;
C. Shared R&D costs: $c_A = 0, c_B = 0$.

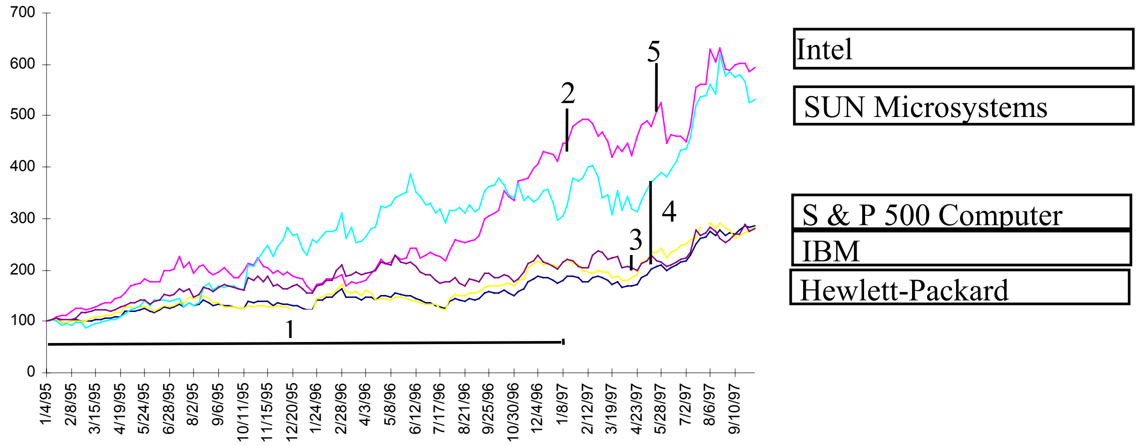
FIGURE 1. Competitive strategies and relative market (price) performance for high-tech firms over a recent two-year period in various industries: A. software, B. computer hardware, and C. consumer electronics

Panel A. Microsoft´s strategic moves and superior market performance over Netscape and other computer software rivals



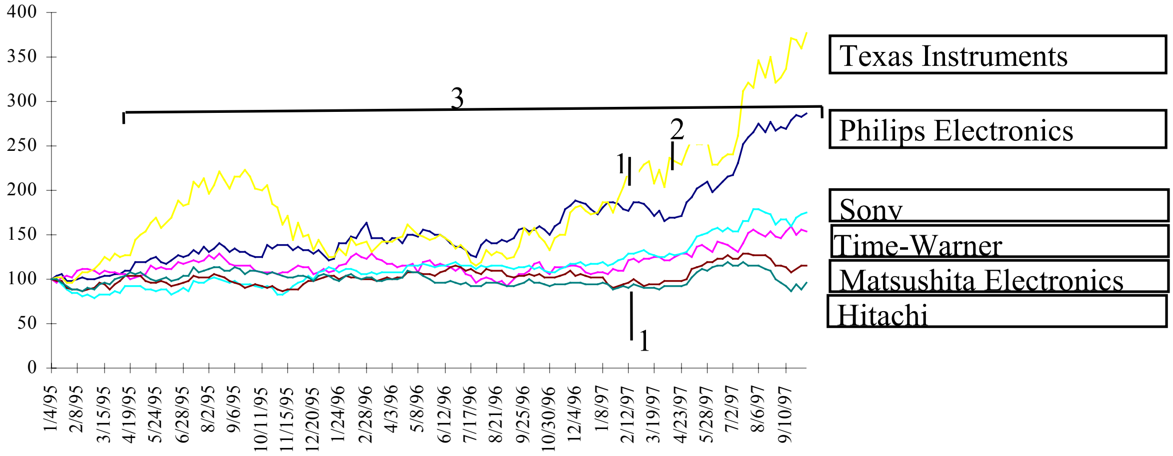
Notes:
1. In August 1995 Netscape goes public in providing software for the Internet (all firms indexed at 100 on 8/9/95).
2. In March 1997 Microsoft allies with rival Hewlett-Packard to push its Windows NT program into corporate servers.
3. In April 1997 Microsoft agrees to buy WebTV, a start-up company that delivers Internet information directly to television sets.
4. In May 1997 Microsoft announces an all-out attack into the lucrative heavy-duty corporate computing market.
5. Also in May 1997 Oracle buys into Navio Communications, established by Netscape to develop Internet software for consumer electronics.
6. Netscape and Microsoft make further strategic moves to gain an advantage in their continuing battle over who will be the Internet standard bearer. Through its superior strategic moves Microsoft gains a clear advantage over Netscape whose relative position is eroding, as confirmed by above market valuation.

Panel B. Superior market performance of Intel and Sun Microsystems over IBM, Hewlett-Packard and other computer hardware rivals



Notes:
1. Intel gets established as the product standard in the microprocessor market with its Pentium chip.
2. In January 1997 Intel moves aggressively in networking products (and in April announces further investment), forcing competitors to reduce their prices (Novell announces 18% cut in its workforce in May).
3. In April 1997, Hewlett-Packard agrees to buy Verifone, leading maker of credit card authorization devices, for its growth potential to dominate the emerging electronic commerce business.
4. In May 1997 Microsoft announces an all-out attack into the lucrative heavy-duty corporate computing market, at the expense of IBM, Sun Micosystems and Oracle. IBM responds aggressively, claiming this to be Microsoft´s “Vietnam”.
5. Also in May 1997 Intel announces its next-generation microprocessor, the Pentium II.
A week later, Digital sues Intel charging remarkable similarities with its Alpha chip.

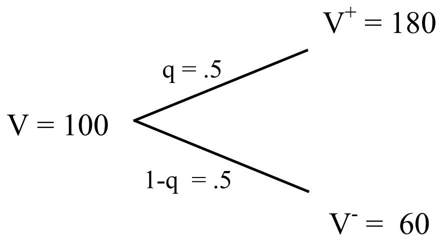
Panel C. Superior market performance of Texas Instruments and Philips over Sony, Time-Warner, Matsushita and other rivals in consumer electronics



Notes:

1. In February 1997 Texas Instruments, Hitachi and Mitsubishi announce they would jointly develop a one-gigabyte DRAM.
2. In April 1997 Texas Instruments gambles on Digital TV with its light processing technology (turning heads in technology circles although currently loosing money), as part of a new higher-risk, higher-margin strategy.
3. Philips and Sony's strategy to commercialize the Digital Video Disk faces competitive pressures by Toshiba and Time-Warner. In 1995 the alliance of Philips and Sony (that developed the Multi-Media CD) agreed with the alliance of Toshiba and Matsushita (that developed the Super-Density Disk) to set a common industry standard for the new-generation high-density CD (the Digital Video Disk). Since then there is an ongoing fight between these manufacturers in dividing the market pie to maximize the value of their investment in the product standard.

FIGURE 2. Static NPV (no surprise or flexibility to deviate from expected scenario): *invest now*



Investment: $I = 80$
Discount rate: $k = .20$
Risk-free rate: $r = .08$
Actual probability: $q = .5$
Risk neutral prob.:

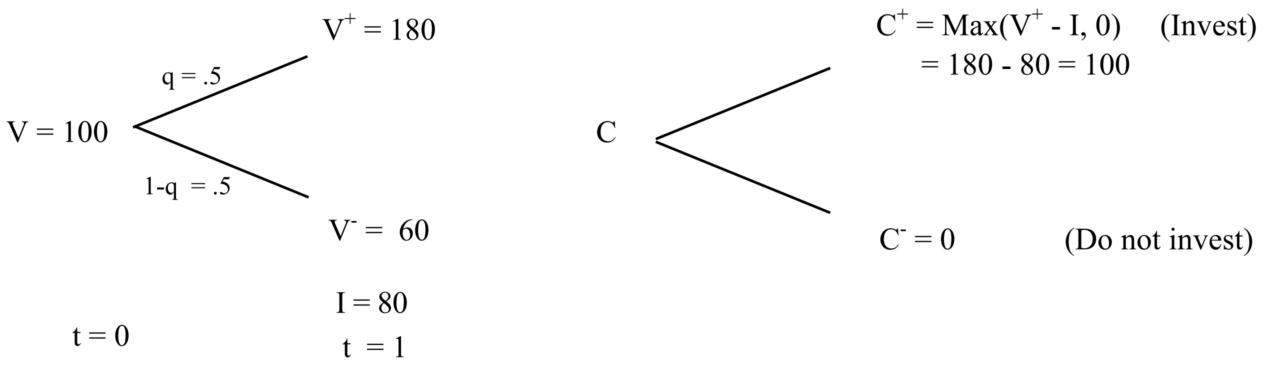
$$p = \frac{(1+r)V^{+} - V^{-}}{V^{+} - V^{-}} = 0.4$$

(Gross) Project value:

$$V_0 = \frac{p \times V^{+} + (1-p)V^{-}}{1+r} = \frac{0.4 \times 180 + 0.6 \times 60}{1.08} = \frac{q \times V^{+} + (1-q)V^{-}}{1+k} = \frac{0.5 \times 180 + 0.5 \times 60}{1.20} = 100,$$

Invest now (commitment value): NPV = V - I = 100 - 80 = 20 (> 0)

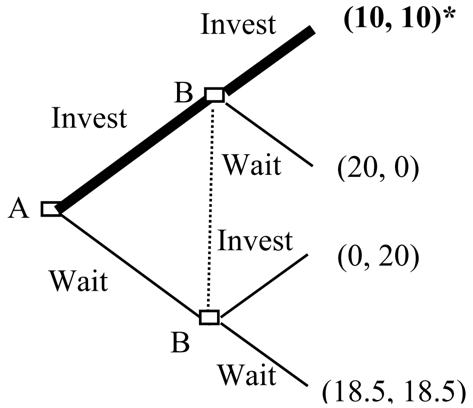
FIGURE 3. Proprietary *opportunity (license)*: *wait* to invest under uncertainty



Opportunity to invest provided by license (call option): $C = \frac{p \times C^+ + (1-p) \times C^-}{1+r} = \frac{.4 \times 100 + .6 \times 0}{1.08} = 37$

FIGURE 4. *Simultaneous* investment timing game: *compete and invest prematurely* (prisoners' dilemma)

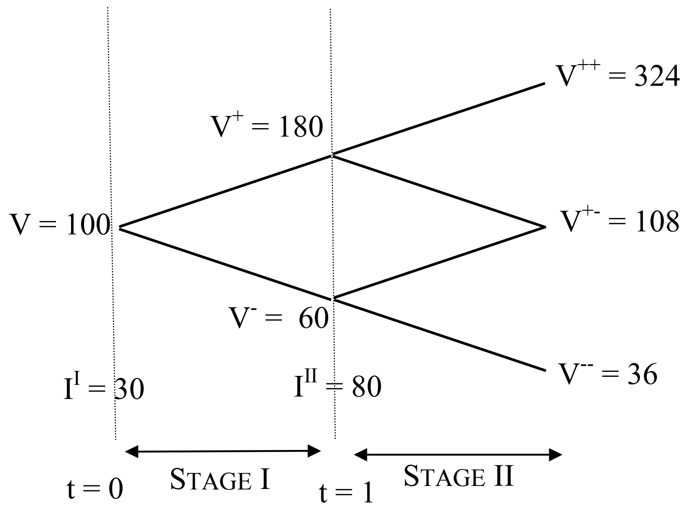
Extensive form



Normal form

		Firm B	
		Wait	**Invest**
Firm A	**Wait**	(18.5, 18.5)	(0, 20)
	Invest	(20, 0)	**(10, 10)***

FIGURE 5. Two-stage investment (e.g., R&D /infrastructure/growth option)



$$NPV = NPV^{I} + NPV^{II}$$
$$= -30 + \left(\frac{-80}{1.08} + \frac{.5 \times 180 + .5 \times 60}{1.20}\right)$$
$$= -30 + (-74 + 100) = -30 + 26 = -4 \ (< 0)$$

$$NPV^{*} = NPV^{I} + Option^{II}$$
$$= -30 + \left(\frac{.4\,(180 - 80) + .6 \times 0}{1.08}\right)$$
$$= -30 + 37 = +7 \ (> 0)$$

FIGURE 6. Competitive strategies depending on type of investment (proprietary vs. shared) and nature of competitive reaction (substitute vs. complement)

		COMPETITION (B)	
		Strategic Substitute (fixed market value) e.g., Quantity competition	***Strategic Complement*** (altered market value) e.g., Price competition
PIONEER (A)	***Proprietary*** (capture most of total market value)	**commiting and offensive** Preemptive commitment (+) effect 1	**flexible and inoffensive** Non-provoking (-) effect 2
	Shared (share total market value)	**flexible and offensive** Vulnerable (-) effect 4	**commiting and inoffensive** Cooperative commitment (+) effect 3

FIGURE 7. *Proprietary* strategic benefits when competitors are strategic substitutes or complements

A. *Proprietary* benefits $(\frac{2}{3})$ of strategic investment when competitors are *strategic substitutes* (fixed size): *invest in R&D (offensive strategy to preempt)*

High demand ($V^+ = 180$)

Firm A \ **Firm B**	**Wait**	**Invest**
Wait	1 (81, 25)	2 (0,100)
Invest	3 (100, 0)	4 **(80, 20)***

Low demand ($V^- = 60$)

Firm A \ **Firm B**	**Wait**	**Invest**
Wait	1 **(10, 0)***	2 (0, -20)
Invest	3 (-20, 0)	4 (0, -20)

$$NPV_A^* = -30 + \left(\frac{0.4 \times 80 + 0.6 \times 10}{1.08}\right) = -30 + 35 = 5\ ;\ NPV_B^* = 0 + \left(\frac{0.4 \times 20 + 0.6 \times 0}{1.08}\right) = 7$$

$I^I{}_A = 30$; $I^{II}{}_A = 40$; $I^{II} = I^{II}{}_A + I^{II}{}_B = 80$ (if preemption $I^{II}{}_A = I^{II}{}_B = 80$)

---

1 $OPTION_A = \frac{0.4 \times (\frac{2}{3} \times 324 - 40) + 0.6 \times (1 \times 108 - 80)}{1.08} = 81$

2 $NPV_A = 0$

3 $NPV_A = 180 - 80 = 100$

4 $NPV_A = \frac{2}{3} \times 180 - 40 = 80$; $NPV_B = \frac{1}{3} \times 180 - 40 = 20$

1 $OPTION_A = \frac{0.4 \times (1 \times 108 - 80) + 0.6 \times (0)}{1.08} = 10$

2 $NPV_A = 0$

3 $NPV_A = 60 - 80 = -20$

4 $NPV_A = \frac{2}{3} \times 60 - 40 = 0$; $NPV_B = \frac{1}{3} \times 60 - 40 = -20$

B. *Proprietary* strategic investment $(\frac{2}{3})$ when competitors are *strategic complements* $(-\frac{1}{4})$: *do not invest in R&D (inoffensive strategy to avoid intensified rivalry and price war)*

High demand ($V^+ = 180$)

Firm A \ **Firm B**	**Wait**	**Invest**
Wait	1 (61, 15)	2 (0,100)
Invest	3 (100, 0)	4 **(50, 5)***

Low demand ($V^- = 60$)

Firm A \ **Firm B**	**Wait**	**Invest**
Wait	1 **(10, 0)***	2 (0, -20)
Invest	3 (-20, 0)	4 (-10, -25)

$$NPV_A^* = -30 + \left(\frac{0.4 \times 50 + 0.6 \times 10}{1.08}\right) = -30 + 24 = -6\ \ (< 0)\ ;\ NPV_B^* = 0 + \left(\frac{0.4 \times 5 + 0.6 \times 0}{1.08}\right) \approx 2$$

---

4 $NPV_A = \frac{2}{3} \times \left(\frac{3}{4} \times 180\right) - 40 = 50$; $NPV_B = \frac{1}{3} \times \left(\frac{3}{4} \times 180\right) - 40 = 5$ 4 $NPV_A = \frac{2}{3} \times \left(\frac{3}{4} \times 60\right) - 40 = -10$; $NPV_B = \frac{1}{3} \times \left(\frac{3}{4} \times 60\right) - 40 = -25$

FIGURE 8. *Shared* benefits of strategic investment when competitors are strategic complements or substitutes

A. *Shared* strategic benefits $(\frac{1}{2})$ when competitors are *strategic complements* $(+\frac{1}{4})$:
invest in strategic project (share expanded pie from coordination)

High demand ($V^+ = 180$)

Firm A \ Firm B	Wait	Invest
Wait	1 (75, 75)	2 (0,100)
Invest	3 (100, 0)	4 **(73, 73)***

Low demand ($V^- = 60$)

Firm A \ Firm B	Wait	Invest
Wait	1 **(10, 10)***	2 (0, -20)
Invest	3 (-20, 0)	4 (-3, -3)

$$NPV_A^* = -30 + \left(\frac{0.4 \times 73 + 0.6 \times 10}{1.08}\right) = -30 + 33 = +3 \ (>0); \quad NPV_B^* = 0 + 33 = +33$$

$$1\ OPTION_A = \frac{0.4 \times (\frac{1}{2} \times \frac{5}{4} \times 324 - 40) + 0.6 \times \left(\frac{1}{2} \times \frac{5}{4} \times 108 - 40\right)}{1.08} = 75$$

$$4\ NPV_A = NPV_B = \tfrac{1}{2} \times \left(\tfrac{5}{4} \times 180\right) - 40 = 73$$

$$1\ OPTION_A = \frac{0.4 \times (\frac{1}{2} \times \frac{5}{4} \times 108 - 40) + 0.6 \times (0)}{1.08} = 10$$

$$4\ NPV_A = NPV_B = \tfrac{1}{2} \times \left(\tfrac{5}{4} \times 60\right) - 40 = -3$$

B. *Shared* strategic benefits $(\frac{1}{2})$ when competitors are *strategic substitutes* (1):
do not invest in R&D (avoid subsidizing *aggressive* competitor)

High demand ($V^+ = 180$)

Firm A \ Firm B	Wait	Invest
Wait	1 (53, 53)	2 (0,100)
Invest	3 (100, 0)	4 **(50, 50)***

Low demand ($V^- = 60$)

Firm A \ Firm B	Wait	Invest
Wait	1 **(5, 5)***	2 (0, -20)
Invest	3 (-20, 0)	4 (-10, -10)

$$NPV_A^* = -30 + \left(\frac{0.4 \times 50 + 0.6 \times 5}{1.08}\right) = -30 + 21 = -9 \ (<0); \quad NPV_B^* = 0 + 21 = +21$$

$$1\ OPTION_A = \frac{0.4 \times (\frac{1}{2} \times 324 - 40) + 0.6 \times \left(\frac{1}{2} \times 108 - 40\right)}{1.08} = 53$$

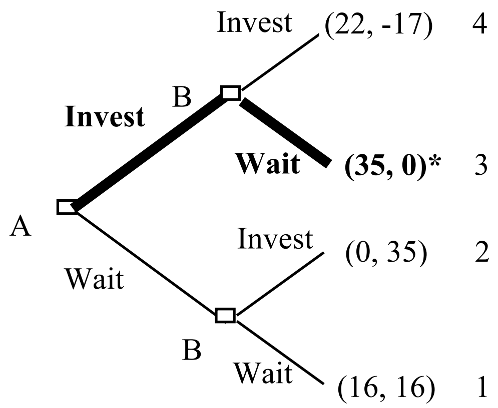
$$4\ NPV = \tfrac{1}{2} \times 180 - 40 = 50$$

$$1\ OPTION_A = \frac{0.4 \times (\frac{1}{2} \times 108 - 40) + 0.6 \times (0)}{1.08} = 5$$

$$4\ NPV = \tfrac{1}{2} \times 60 - 40 = -10$$

FIGURE 9. Both firms can make strategic (e.g., R&D) investment in the first stage enhancing market value $(\frac{5}{4})$: R&D *competition*

A. *Sequential* R&D investment race: invest to preempt
($(\frac{2}{3})$ first-mover or time-to-market advantage)



		Firm B	
		Wait	**Invest**
Firm A	**Wait**	1 (16, 16)	2 (0, 35)
	Invest	3 **(35, 0)***	4 (22, -17)

---

1 $NPV_A^* = NPV_B^* = \frac{0.4 \times (43) + 0.6 \times 0}{1.08} = 16$

2,3 $NPV^* = \left(\frac{0.4 \times (\frac{5}{4} \times 180 - 80) + 0.6 \times 20}{1.08} \right) - 30 = 35$

4 $NPV_A^* = NPV^I + OPTION^{II} = -30 + \left(\frac{0.4 \times 110 + 0.6 \times 20}{1.08} \right) = 22\ (> 0);\ \ NPV_B^* = -30 + \left(\frac{0.4 \times 35 + 0.6 \times 0}{1.08} \right) = -17$

B. *Simultaneous* R&D investment battle: invest prematurely (prisoners' dilemma)

		Firm B	
		Wait	**Invest**
Firm A	**Wait**	1 (16, 16)	2 (0, 35)
	Invest	3 (35, 0)	4 **(2, 2)***

---

4 Both firms invest simultaneously (share equally expanded benefits):

$$NPV_A = NPV_B = \frac{0.4 \times (\frac{1}{2} \times \frac{5}{4} \times 180 - 40) + 0.6 \times 10}{1.08} - 30 = 32 - 30 = 2$$

FIGURE 10. *Cooperate* in technology investment (innovation): joint R&D ventures

		Firm B	
		Wait	**Invest**
Firm A	**Wait**	1 **(22, 22)***	
	Invest		4 (17, 17)

---

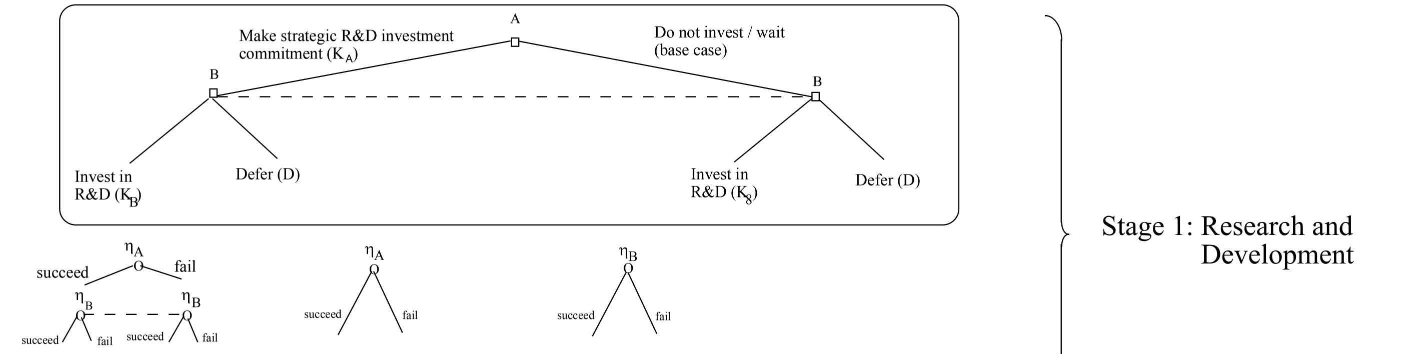
1. OPTION $= 16 + \dfrac{0.4 \times 15 + 0.6 \times 0}{1.08} = 22$

4. NPV $= 2 + 15 = 17$

Figure 11. The Basic Two-stage Investment Game, Involving R&D and Commercialization Phase under Different Market Structures

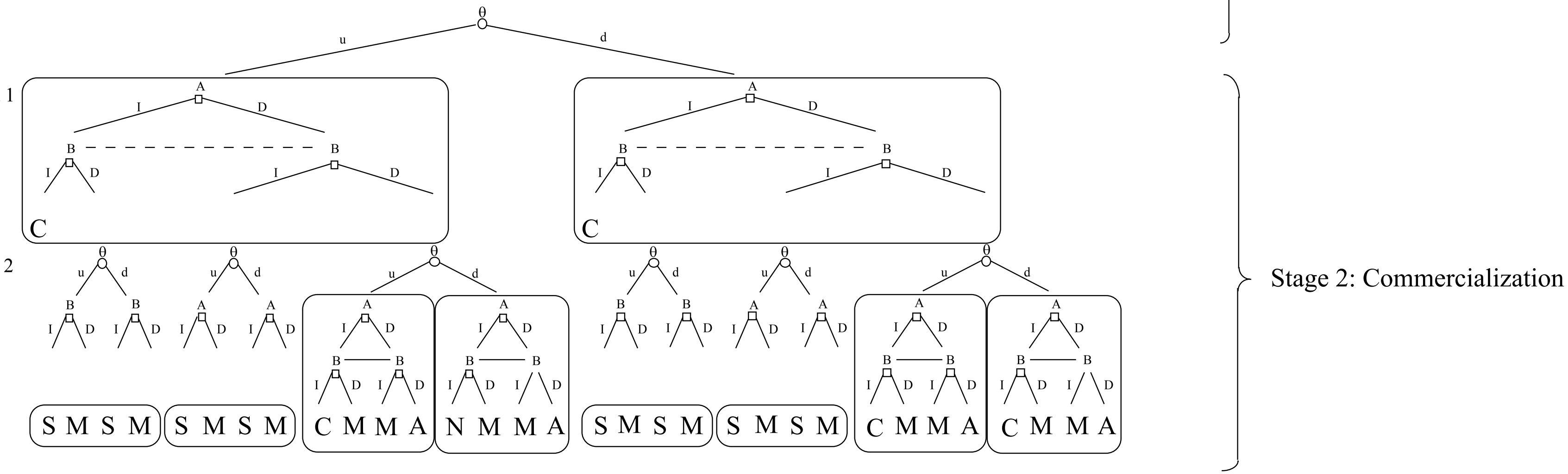
Panel A. R&D competition

Period 0



Notes A or B (0) represents a decision to invest (K) in R&D or defer (D) by form A or B (η) represents technical uncertainty.

Panel B. Commercialization

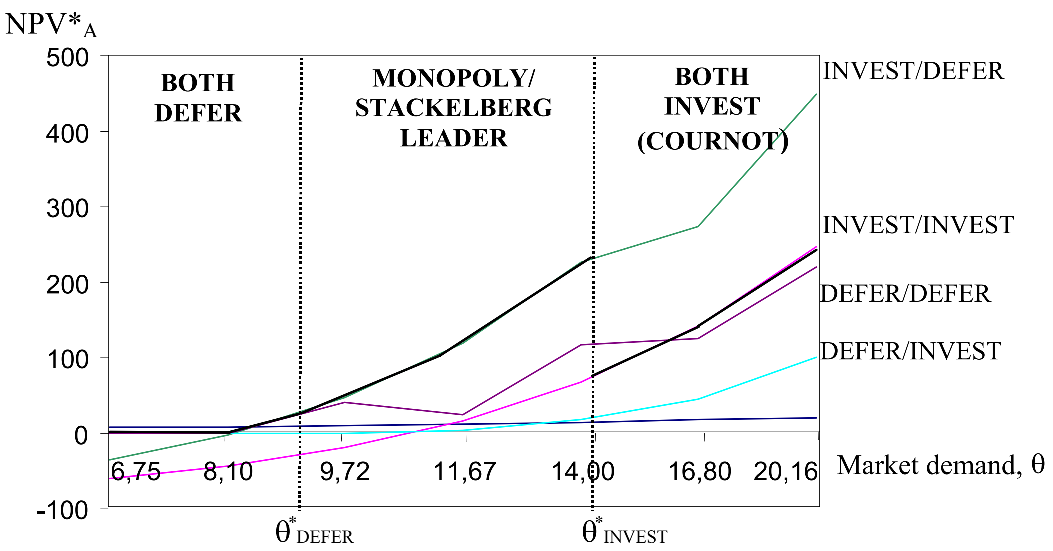


Notes: A or B (□) represents a decision to invest (I) or defer (D) by firm A or B.
θ(○) represents the state of market demand or nature's up (u) and down (d) moves.

The combination of competitive decisions (A or B) and market demand moves (θ) may result in one of the following market structure game outcomes:
C: Nash Cournot quantity competition equilibrium outcome
S: Stackelberg leader (S^L)/ follower (S^F) outcome
M: Monopolist outcome
A: Abandon (0 value)

FIGURE 12. Expanded Net Present Value for Firm A (NPV^*_A) in the commercialization stage (at t = 1) vs. market demand (θ) (upper Panel) and volatility vs. market demand (θ) (lower Panel) illustrating critical demand zones for various competitive strategies for proprietary R&D investment.

Panel A. Expanded Net Present Value (NPV_A*) vs. market demand



Panel B. Firm volatilities vs. market demand