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Strategic NPV: Real Options and Strategic Games under Different Information Structures

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Research summary: *Among the most difficult firm strategic choices is the trade-off between making a long-term commitment or holding off on investment in the face of uncertainty. To operationalize strategic management theory under demand, technological and competitive uncertainty, we develop a Strategic Net Present Value (NPV) framework that integrates real options and game theory to quantify value components and interactions at the interface between NPV, real options, and strategic games. Our approach results in new propositions clarifying the way learning-experience conditions, technological uncertainty, and proprietary information interact to tilt the balance in the interplay between wait-and-see flexibility and strategic commitment. As such, Strategic NPV adds to our understanding of the conditions where NPV, real options, or strategic thinking are more relevant.*

Managerial summary: *This study develops and elucidates implementation of a new valuation construct, "Strategic Net Present Value (NPV)," that integrates real options and game theory to more accurately portray strategic decisions underlying management theory. Among the most difficult firm strategic choices in capital intensive industries, such as energy, mining, chip manufacturing, and infrastructure development, is the trade-off between making a long-term commitment or holding off on investment in the face of demand, technological, and competitive uncertainties. The study provides new insights on the way various conditions, such as learning-experience effects, technological uncertainty, and proprietary information, interact to tilt the balance in the interplay between commitment and wait-and-see flexibility. As such, Strategic NPV adds to our understanding of when NPV, real options, or strategic thinking matter more critically for decision making.*
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Strategy is concerned with value creation and value capture in imperfect markets (e.g., Chatain & Zemsky, 2011). Managers in organizations make decisions under conditions of market uncertainty, competitive rivalry, and incomplete information. Value and valuation of a firm or project-level investment is important to the strategic management field as it involves a fundamental trade-off and assessment of the costs and long-term benefits of a strategic initiative. Strategy decision making, especially decisions concerning strategic investments, explicitly or implicitly involves a cost versus benefit/value calculation under such conditions. Management theories such as Transaction Cost Economics (TCE) or agency theory pay attention to cost (value capture, as well as value creation), while Resource-based View (RBV) and related variants like dynamic capabilities (Teece, Pisano, & Shuen,

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1997) and the knowledge-based view (Grant, 1996) give most attention to value creation.[1]

Among the most difficult cost versus value choices firm strategists must make under competition and uncertainty conditions are those that involve making a long-term commitment to a given course of action or alternatively holding off or staging such investments in the face of uncertainty, as the market entry and global expansion of Zipcar exemplifies. Fail to make a commitment in an industry with steep learning-curve or network effects, and the firm might effectively be shut out. Make a commitment too early, and the firm risks missing the eventual market opportunity, technological standard, or materialization of demand. The right balance between commitment and flexibility can prove critical to survival and success. Wernerfelt and Karnani (1987) identified a pressing, yet to this date, unfilled research gap: "Since strategy is concerned with the future, the strategic context of a firm is always uncertain … under uncertainty there is a trade-off between focus [commitment] and flexibility … this analysis is further complicated by the presence of competition … the literature on strategic planning has avoided discussing the trade-offs involved in confronting uncertainty." The strategic management literature has long recognized the importance of the commitment versus flexibility trade-off, but it has provided little guidance on how firms can actually quantify these interactions under both uncertainty and rivalry.

Although extant management theories focus on different sources of cost or value, they are not explicit about what valuation framework they (should) rely on. Traditional Net Present Value (NPV) is disconnected from strategic analysis (e.g., it fails to view the unfolding of strategy in stages as options or to properly account for competitive reactions) and does not capture the inherent tug-of-war between commitment and flexibility. Real options theory is superior in valuing the flexibility or staging dimension under uncertainty, while game theory alone is advantageous in accounting for industry dynamics and competitive interactions under rather predictable conditions. As in most real-life strategic decision contexts, both conditions of market uncertainty and competitive rivalry are concurrently present, a key question is: How can one meaningfully inform strategy decision making on the important interactions between commitment and flexibility. Specifically, this article contributes to strategy research by answering the question: How can the combination of real options theory (that helps quantify the benefits of flexibility) with a game-theoretic approach (that allows analysis of commitment) shed new insight on strategic management?

The article introduces the methodology of "option games" to the strategy field, presents the basic structure of such a model, and illustrates what insights might be gained from the application of this integrative approach to the examination of key strategy questions. The main contribution is to use analytical models—combining real option analysis and game theory—to examine the specific conditions that affect different components of firm value, which in turn affect the aggregate "Strategic NPV," and thus, may shape firms' strategic decisions to invest in innovation or R&D. Our findings shed new light on a number of trade-offs between commitment and flexibility in strategy decision making that improve our understanding of the conditions involving different information structures when NPV, real options, or strategic game-theoretic analysis are more relevant.

Given that value and valuation matter critically to strategy, we develop and elucidate implementation of a new valuation construct, "Strategic NPV," to help build a stronger connection to the strategy field and more accurately portray strategic decisions underlying alternative management theories. This construct, besides accounting for traditional sources of committed value captured in an NPV analysis, also helps bring out the interplay among added sources of value from making a strategic commitment (based on game theory) as well as wait-and-see flexibility (highlighted by real options). By properly integrating real options and game theory, Strategic NPV provides the strategist a more complete representation of the various value components and trade-offs from competing courses of action.[2]

[1] The focus of the new institutional economics theories (including the Williamsonian branch of TCE, property rights theory, and agency theory) is on the efficiency in the organization of economic activities under the supposition that suboptimal organizational choices give rise to perverse incentives and result in the dissipation of value to be created in economic activities. These theories are as much concerned with value creation as with cost efficiency.

[2] This is an extension of "Expanded NPV" developed by Trigeorgis (1996) to capture exogenous (e.g., demand) uncertainty in competitive markets. *Direct NPV* here refers to the value benefits of direct investment, for example, the cost savings that may result from a strategic R&D investment in a superior technological

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$$\text{Strategic Net Present Value } (\text{NPV}^*) = \underbrace{[\text{Direct NPV} + \text{Strategic value}]}_{\text{Commitment value}} + \text{Flexibility value.} \quad (1)$$

Besides the value of expected discounted cash flows (DCF) from preset operations and strategies (direct NPV), Strategic NPV also reflects the dimensions of strategic commitment as well as flexibility value under uncertainty. These two additional value components (besides NPV) are in a dynamic conflict and must be balanced under both competitive as well as market demand uncertainty. The strategic value component of Equation (1) is made up of two subcomponents: (a) *strategic reaction value* (a scale effect), reflecting change in market share and firm value resulting from competitive reaction under a given market structure, and (b) *strategic preemption value* (a timing or first-mover effect) reflecting potential rival preemption shifting the market structure altogether (e.g., from Cournot duopoly to monopoly).

The various Strategic NPV components are seen to be in a dynamic tug-of-war and their role, relevance, and impact are context-dependent under conditions of uncertainty and different information structures. The article specifically models the interplay among technological, competitive, and market uncertainty as well as learning experience effects and proprietary information, and helps delineate the boundary conditions specifying when a strategic investment is best viewed through NPV, real options, or a strategic games lens. It lays out, for instance, how ambiguity about rivals' information set affects the balance between flexibility and commitment as an optimal course of action. Understanding and making these core trade-offs presupposes the strategist's ability to measure these value components and their interactions. Through our simple but integrative framework, we provide a synthesis of important strategy ideas accessible to a wider audience. An additional contribution lies in examining the interactive effects on firm value of key driving factors, namely, uncertainty of various sorts, learning experience effects, and proprietary information. We find that learning not only affects the components of firm value differently than technological uncertainty or proprietary information, but it also interacts heavily (negatively) with technological uncertainty since potential R&D success realization and learning experience effects are effectively mutually exclusive. Strategic NPV thus fills an important gap, enabling the valuation and integration of different theories, value components, and their interactions.

Literature and Information Structure

Our Strategic NPV framework provides guidance to help operationalize and quantify existing strategic management theories, thus serving as an integrating theory. It can therefore empower strategy researchers with the valuation capability to properly assess the conflicting valuation effects and interactions that have challenged strategic management theories. Cost-driven efficiency arguments from TCE and agency theory can be partly captured within direct NPV, although incentive implications also impact on strategic value.[3] Strategic commitment value resulting from first-mover advantages under rivalry was traditionally anchored in industry and competitive analysis, IO, and game theory (Brandenburger & Nalebuff, 1995; Lieberman & Montgomery, 1988; Porter, 1980; Shapiro, 1989).[4] Traditional RBV and core competence arguments (e.g., Penrose, 1959; Rumelt, 1984; Wernerfelt, 1984) are also mostly connected to the commitment value literature.

Flexibility value is firmly grounded in real options theory (Dixit & Pindyck, 1994; Trigeorgis, 1996), and partly accounted for in the dynamic capabilities view (Mahoney, 2005; Teece et al.,

process that lowers future marginal production costs, net of the R&D capital investment cost.

[3] Many models based on the new institutional economic theories also use a game-theoretic approach to study the incentive implications of different organizational structures and mechanisms. The game being played in these models is between two actual or potential collaborators in a production process rather than between two rivals as in the case of this article.

[4] Game theory helps formalize intuitive arguments, such as the role of commitment in R&D competition (Dasgupta & Stiglitz, 1980), patent races, capacity investment, signaling the type of competition (Fudenberg & Tirole, 1984) and the trade-off between commitment and flexibility (e.g., Spencer & Brander, 1992). Since the 1980s, interest grew in game theory applications in strategic management, such as the role of commitment (Boyer, 1997; Ghemawat, 1993; Ghemawat & del Sol, 1998).

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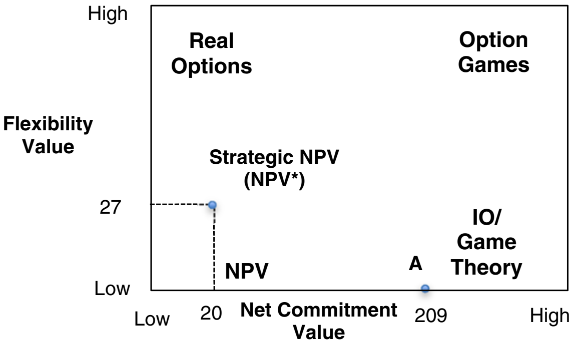

Figure 1. Positioning of Strategic NPV (NPV*) and its extended domain of applicability.

1997). Strategy scholars readily embraced the real options logic for initiating and amplifying "strategic" investments (e.g., R&D, infrastructure, platform, or joint venture ones; see Chi, 2000; Kogut, 1991) leading to follow-on growth options (Bettis & Hitt, 1995; Bowman & Hurry, 1993; McGrath, 1997; McGrath & Nerkar, 2004; Miller & Arikan, 2004; Miltersen & Schwartz, 2004). For a review of real options theory in strategic management, see Trigeorgis and Reuer (2017). Figure 1 reviews the positioning of Strategic NPV (or NPV*) relative to related literatures (NPV, Real Options, IO/Game Theory, Option Games) and illustrates its extended applicability domain along the core flexibility and (net) commitment value dimensions.

The option games literature at the intersection of real options and IO/game theory (in the upper right corner of Figure 1) has explicitly recognized that competitive forces may provide an incentive to exercise options early, emphasizing the first-mover advantages of early commitment (e.g., Chevalier-Roignant & Trigeorgis, 2011; Folta & O'Brien, 2004; Grenadier, 1996; Kester, 1984; Lambrecht, 2004; Miller & Folta, 2002; Smit & Ankum, 1993; Smit & Trigeorgis, 2004; Trigeorgis, 1993a, 1996). Kulatilaka and Perotti (1998) treated preemptive investment as creating a strategic growth option. For investments involving such growth options, uncertainty and rivalry can tilt the balance toward early investment commitment (Folta & O'Brien, 2004).

Since discounted cash-flow (DCF or NPV), commitment, and flexibility arguments each have a sound theoretical justification in strategy, a key question is: How should they meaningfully inform strategy decision making and when is each approach more appropriate? Strategic NPV helps fulfill an important function in valuing the above core components and interactions, and thereby, providing an integration of relevant theories, serving as a "compass" to uncover the basic conditions when NPV, commitment, and flexibility are most relevant. Our work extends related literature in understanding how learning experience effects, different types of uncertainty and proprietary information and ambiguity about rivals' characteristics interact to tilt the balance between flexibility and commitment.

Unlike early real option models that emphasized the value of deferral (Dixit & Pindyck, 1994; McDonald & Siegel, 1986; Trigeorgis, 1996), we show that in a competitive context learning experience effects, previously known to favor early commitment (to accumulate experience) and sacrifice flexibility value for a monopolist (Majd & Pindyck, 1987), acquire additional strategic importance via interactions involving a preemption benefit when keeping out the rival eliminating its learning-cost advantage, giving more relevance to strategic games relative to the flexibility view.

Our study also places new emphasis on the interplay between technological uncertainty and market uncertainty (see Oriani & Sobrero, 2008) under competitive rivalry conditions, and uncovers value shifting interactions between the core Strategic NPV components. While technological uncertainty involving the risk of failure is known to favor wait-and-see flexibility in R&D investment for a monopolist, we show that under rivalry the risk of technological failure helps balance opposing effects and mitigates the nonmonotonic impact of market uncertainty on preemption. As a result, the Strategic NPV compass reverts back from strategic games to real options.

Finally, we show how proprietary information and rival information ambiguity help shape the conflicting balance between flexibility and early commitment. It has been known that adverse information about demand discourages entry into a new market (McGahan, 1993) and that firms avoid revealing positive proprietary information about their growth options to potential entrants (Turut & Ofek, 2012). We extend these ideas in a competitive incomplete-information context, showing how proprietary information concerning the success or failure of a rival's R&D efforts affects the interplay between NPV, flexibility, and strategic value components, tilting the analysis back toward NPV.

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An additional contribution of our option games analysis is the ability to model the interactive effects of two or more such information structure factors on firm value. Trigeorgis (1993b) showed that when real options involve redundancy (e.g., put-type options such as to contract, switch use, or abandon all paying off in adverse conditions), they may be worth much less than the sum of separate values. In the strategic management literature, Vassolo, Anand, and Folta (2004) examined this idea in the context of biotech alliances, while Belderbos, Tong, and Wu (2014) examined it in the context of multinational investment. Makadok (2010) studied the interaction effects of rivalry restraint and competitive advantage on firm profits and found a strong negative interaction due to a plausible inconsistency to pursue both of these pathways to profit concurrently. We find an analogous negative interaction effect here due to mutual exclusivity among learning experience and technological uncertainty effects in case of R&D success. In the empirical real options literature, several studies, such as Folta and O'Brien (2004), Tong and Li (2011), and others (e.g., Anand, Oriani, & Vassolo, 2007; Oriani & Sobrero, 2008; Vassolo et al., 2004), have examined interactive effects of growth versus deferral options, deferral options interacting with product market competition, interactive effects of different types of uncertainty or the impact of learning/capabilities on firm value. However, these studies are not able to disaggregate or calibrate different value components as we do. Ours is the first study that actually calculates interaction effects involving the commitment-flexibility trade-off in a real options context, concurrently involving learning, technological uncertainty, and information asymmetry. Our strategic NPV construct thereby helps synthesize and integrate diverse perspectives from different management theories and helps quantify the interactions among conflicting value components in different information structure conditions.

Strategic NPV: Applications and Illustration of Basic Components

We next discuss some applications in various sectors and illustrate the type of real options and games analysis involved in valuing the separate Strategic NPV components of Equation (1). In urban land, for instance, developers with proprietary rights often defer development until the best future use is more evident (Titman, 1985). But when fearing preemption by rivals, competitive pressure to develop often results in early development. Sometimes this results in overcapacity and industry equilibria involving "boom-and-bust" cycles (Grenadier, 1996). Similar trade-offs are prevalent in the context of European airport expansion, where investment is irreversible, lumpy, and capacity modules to deter rival airport expansion are critical (Smit & Trigeorgis, 2009). In CD commercialization, Philips preempted Sony by building a larger plant (McGahan, 1994). In situations involving the threat of rival preemption, uncertainty often leads to earlier investment (Miller & Folta, 2002). The need for an explicit valuation to support acquisition bids makes Strategic NPV applicable to serial M&A strategies (Smit & Moraitis, 2010, 2015).

In energy and mining, new technology platform investments enable energy companies to obtain preferential access to new resource opportunities, develop renewables, and squeeze more out of older fields. Floating gas platforms reduce operating costs and strengthen the firm's strategic position in bidding on future gas prospects. Shell invested \$11.5B in its Prelude LNG project in Australia, the world's first floating-LNG plant, enabling the firm to pursue future offshore gas fields that are too costly with existing technology. Such investment provides cost savings (*direct NPV*) and preemptive advantages in bidding for new fields (*strategic preemption effect*). In light of technological uncertainty and volatile energy prices, Shell has made a strategic commitment to secure future resources.

Chip manufacturing also involves large lumpy investments in production capacity facing uncertain growth in world demand. Key supplier ASML invited its largest customers, Intel and Samsung to invest \$1.5B each in Extreme Ultra Violet (EUV) lithography. This technology investment would sacrifice flexibility value in the midst of uncertain demand traded off against the risk of being locked out of the new technology. If rival chip producers decide to share the new innovation (EUV technology), cost heterogeneity and preemption advantages may effectively be eliminated.

Depending on the industry context, differences in information structure might dramatically shift the above trade-offs and interactions between value components. For instance, the presence of learning

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cost benefits may tilt the balance toward early commitment, but technological uncertainty in the innovation stage may erode early preemption value.[5] We next discuss intuitively and illustrate via a simplified example the Strategic NPV framework underlying Equation (1) and Figure 1, and the basic building blocks underlying real options and game theory.

Investment (Timing) Under Uncertainty: Direct NPV and Flexibility Value (Real Options)

Suppose a high-tech firm like Intel has an opportunity to build plant capacity next year that involves a $I_0 = \$100M$ lump-sum outlay today (at $t = 0$). The current (gross) value of expected future cash inflows is estimated at $V_0 = 120M$. The standard net present value of investing immediately (at $t = 0$) is $NPV_0 = V_0 - I_0 = 120-100 = 20M$ (>0); this payoff would lead to immediate investment commitment (at $t = 0$). NPV, however, is unable to properly capture the flexibility value dimension.

Real options (upper left in Figure 1) goes a step further to incorporate the flexibility value to delay or adjust prospective decisions under uncertainty. Suppose Intel's proprietary opportunity is to commercialize a sleeping patent utilizing existing technology that expires in 1 year ($t = 1$), providing valuable flexibility not to invest in the plant if uncertainty resolves unfavorably next year. The proprietary opportunity to invest is analogous to a call option on the value of the developed completed project (V), with an "exercise price" the investment outlay to build plant capacity ($I = \$100M$). The option value of the proprietary opportunity to invest within a year provided by the patent (estimated at $C_0 = \$47M$)[6] here exceeds the NPV of immediate commitment ($C_0 > NPV_0$ as 47 > 20). If Intel could wait for a year under demand uncertainty, Strategic NPV or NPV^* (as given by real options analysis here) would equal \$47M. Based on Equation (1), this strategic value (47) consists of the passive NPV of existing technology (of 20) and an incremental wait-and-see flexibility value (of 27):

$$\begin{aligned} &\text{Strategic NPV (existing technology)} \\ &= \text{Passive NPV} + \text{Flexibility value} \\ &= 20 + 27 = 47\text{M}. \end{aligned}$$

That is, the opportunity for Firm A to defer commercializing the old technology (from its sleeping patent) up to a year ($t = 1$) results in an enhanced total value of \$47M. This is the valuation given by real options analysis (alone). The NPV and flexibility values are depicted along the horizontal and vertical axes of Figure 1. There is no strategic value from staying with the old technology.

Incorporating Rivalry: Commitment Value in New Technology (Game Theory)

Technology firms like Intel and rival Samsung commonly face investment decisions to add capacity using existing or by investing in new technology to remain competitive. Beyond the flexibility value to wait to invest (relying on existing technology) driven by market uncertainty regarding chip demand addressed by standard real options analysis, we must now account for the strategic investment commitment to the new technology that could lower future production costs and gain ground on competition. By investing in the new technology, flexibility value would be given up

[5] Learning experience with intricate and complex tasks is significant in industries ranging from shipbuilding and airplane manufacturing to consumer electronics and the design and production of software. Such learning benefits may tilt the decision toward early commitment. Technological uncertainty is important in sectors ranging from pharmaceuticals to high tech, shifting the balance more toward wait-and-see or staging flexibility. Interaction between technological and market demand uncertainty is important in fields such as mining and energy, where exploration uncertainty interacts with uncertainty in commodity prices. It is also important in new ventures in high-tech (McGrath, 1997) and industries focused on next-generation technologies such as computers, tablets, or cell phones, in pharmaceutical R&D and in the biotech industries (Folta & Miller, 2002) where technological preemption and demand uncertainty are important.

[6] For the interested or mathematically-inclined reader, we here assume the value of expected cash flows V (with $V_0 = 120M$) fluctuates with random fluctuation in demand, say to $V^+ = 243M$ or $V^- = 69M$ by $t = 1$. The opportunity to invest (at an assumed fixed cost of $I = 100M$) provided by the proprietary sleeping patent is more valuable than immediate investment commitment at $t = 0$ since it allows the option to defer investment for a year and invest then only if market developments are favorable (worth at $t = 1$ $NPV^+ = V^+ - I = 243 - 100 = 143M$ or wait and see (with assumed continuation value of $NPV^- = 9.5M$) under unfavorable developments. The value of this strategic investment opportunity (Strategic NPV or NPV^*), seen as a call option on future completed and operating added plant capacity, can be derived from the end-of-period option payoff values (with expectations taken over the up and down risk-adjusted probabilities, here $p = 0.3$ and $1 - p = 0.7$), discounted at the risk-free rate ($r = 0.05$) as: NPV_0^* or $C_0 = [p \times NPV^+ + (1-p) \times NPV^-]/(1 + r) = [0.3 \times 143 + 0.7 \times 9.5]/1.05 = 47M$.

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for the strategic benefits associated with strategic reaction and preemption effects, discussed next.

Suppose Intel (henceforth, Firm A) considers a similar opportunity to enhance its competitive position in the production of computer chips by committing now (at $t = 0$) to developing a new technology to lower its future production cost via a strategic R&D investment (with estimated cost \$100M). The total strategic NPV of the decision to develop the new technology is estimated at \$229M. This value consists of the base-case passive NPV of using the old technology of 20M (= 120−100) plus a net strategic commitment value estimated at \$209M. The latter results from several components: The direct NPV (new) of extra cost savings of the new over the old technology plus the strategic reaction and preemption value arising from both gaining market share and potentially preempting the rival (flexibility is given up here to gain the benefit from commitment). Thus,

$$\begin{aligned}
&\text{Strategic NPV (new tech)} = \text{Base NPV (old)} \\
&+ \big[\text{NPV (new)} + \text{Strategic reaction \& preemption} \\
&\quad \text{value} + \text{Flexibility value}\big]. \\
&= \text{Base NPV (old)} + [\text{Net commitment value}] \\
&= 20 + 209 = 229\,\text{M}. \qquad (1)
\end{aligned}$$

This strategic NPV of \$229M is estimated herein by extending the real options analysis with basic game theory via "option games" (see also Smit & Trigeorgis, 2004), depicting the interaction of market uncertainty (evolving in a binomial option tree) and strategic rivalry (depicted via 2 × 2 payoff games). A two-period illustration among Firm A and its rival (Firm B) is provided in Figure 2, where Firm A can choose to invest in the new technology (upper path) or stay with the old technology (lower path). With the new technology, each firm can decide at $t = 1$ to invest (I) or defer (D) in production capacity, resulting in the four scenarios with different product market characteristics and payoff values shown in Figure 2. A different 2 × 2 game results at each time and level of demand (θ) as it moves up or down.

Solving this game involves three main steps: (a) estimating the payoffs for each firm, (b) deriving the optimal strategy in each 2 × 2 game using game theory principles, and (c) performing backward valuation of the future equilibrium payoffs to obtain the current value using option theory. The first step, starting from the end, involves determining the payoff values for each rival, (Firm A, Firm B), based on industrial organization models. How the product market (payoff) values in Step 1 are derived (e.g., when one firm has an advantage) is explained in the next section. The second step in game theory analysis is to identify dominant strategies, giving a higher payoff to a firm than any alternative action whatever the rival decides, and then determine the Nash equilibria in each 2 × 2 subgame from which neither player has an incentive to deviate. For instance, in the (blown-up) 2 × 2 game in the scenario when demand (θ) is down (d) in period $t = 1$ under the new technology alternative in Figure 2, the Nash equilibrium outcome is (Invest, Defer) in cell *ii* resulting in equilibrium payoff values $(272, 0)^*$.[7] The third step uses option valuation procedure to work backward to $t = 0$ taking the expectation over next-period state equilibrium outcomes ($t = 1$ payoff values). The current value of the equilibrium strategy (of 229M) captured in Strategic NPV in Equation (1) reflects the strategic values arising from competitive interactions in future demand states in industry equilibrium. In the resulting equilibrium strategy, Firm A would find it preferable to invest in the new technology rather than defer adoption staying with the old technology (229 > 47). This allows Firm A to optimally realize *reaction value* from gaining a larger market share at high demand [when both firms invest (II)] while *preempting* the opportunity earning (temporary) monopoly profits in low demand (ID). Details of the backward option games process of Step 3 are given in the next section.

Basic Option Game Model

The previous numerical example involved simplification of the competitive situation to illustrate and put flesh on the Strategic NPV construct of Equation (1). We next analyze a more comprehensive model set up that better describes IO/product market competition that will form the basis for our subsequent extensions into different information

[7] In the above subgame (at $t = 1$ when demand $\theta = \text{d}$) in Figure 2, Firm A has a dominant strategy to invest (I) regardless of what Firm B decides to do (A would receive 209 > 153 if B invests, or 272 > 234 if B defers). Analogously, Firm B has a dominant strategy to defer (D) regardless of what Firm A decides (receiving 0 rather than −86 if A invests, or 0 > −65 if A defers).

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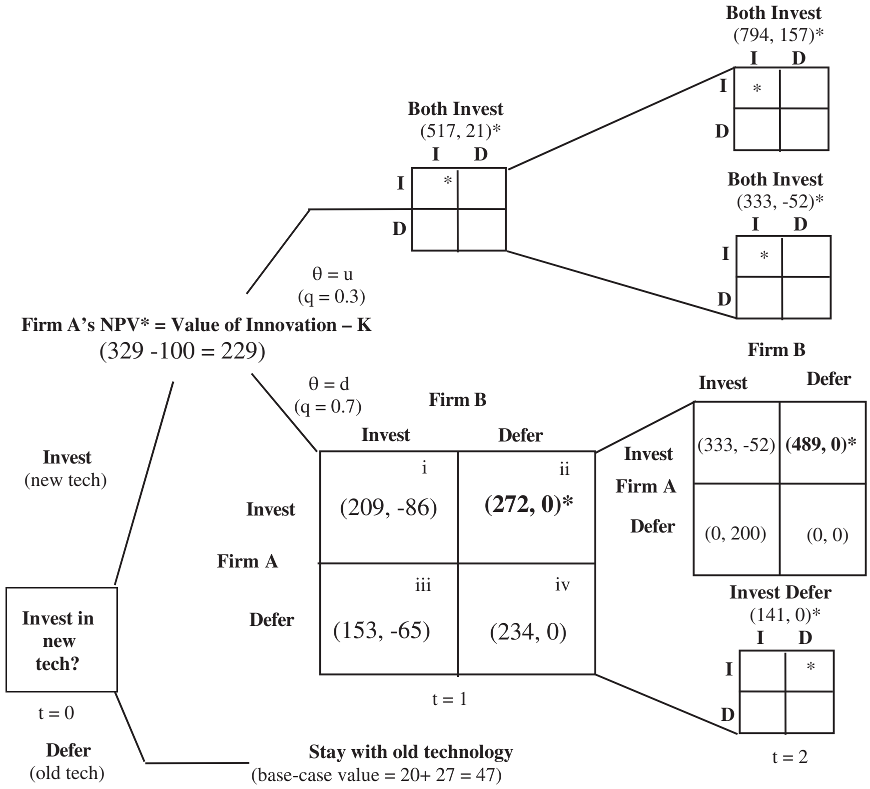

Figure 2. Two-period illustration of backward option-games valuation.

structures. In this setup, Firm A can make a strategic innovation investment in the first stage (R&D) that can shape the strategic position of the firm vis-à-vis its rival (Firm B) in the product market (second stage). Firm A's strategic R&D investment value depends on endogenous investment timing and output decisions by both firms. It can create or enhance cost asymmetries, thereby interacting with market structure via altering the competitor's equilibrium quantity or changing the market structure altogether, for example, by preempting the rival. Firm A can reduce its future operating cost either by investing in the new process innovation or by gaining experience through cumulative production (learning cost effects) using existing technology. Firm B can reduce its future costs only by expanding production using the old technology. The resulting cost heterogeneity among rival firms, depending on their choices and demand evolution, gives rise to investment timing differences (e.g., resulting in a sequential leader-follower game) or it may result in a preemption equilibrium, depending on demand and the relative first-mover technological cost advantage.

Figure 3 outlines our basic model setup for a two-stage duopoly investment game.[8] Stage 1 represents the innovation (R&D) stage, and Stage 2 the launch or commercialization phase.[9] In Stage 1 (period 0) Firm A must decide whether to make an R&D investment commitment in the new technology (incurring cost K_A) or not to invest, that is, to wait and stay with the old technology (base case). In Stage 2, alternative actions faced by each firm i (i = A, B) to make a commercialization investment (I) in plant capacity or to defer (D) capacity investment till next period are shown by squares (□). Exogenous market demand shocks (θ) representing fluctuations in market demand or nature's up (u) and down (d) moves along a binomial tree are represented by circles. Different combinations of

[8] In the current theorization, the flexibility value part of Strategic NPV is more focused on growth option value as this is particularly helpful for our (simplified) numerical analysis, though flexibility value is broader (e.g., in the MNC context, it may take the form of a network of across-country switch options).

[9] The addition of more stages per se (without altering the essential structure of the model) would not qualitatively alter the model predictions even though certain discontinuities may be less pronounced.

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market demand (θ) realizations along the binomial tree and simultaneous or sequential invest (I) or defer (D) capacity decisions by each rival result in different duopoly type games (Cournot C, Monopoly M, Stackelberg S, Abandon A) at the end states (entering steady-state after period 2). The equilibrium quantities (Q^*) and project values (Strategic NPVs) in the end states at period 2 (or 1) in various market structures (C, M, S, A) are summarized in Table 1.

The value payoffs for Firms A and B are derived in each of four types of scenarios arising from their staged decisions to invest now (I) or defer (D): (a) both firms invest simultaneously (II) resulting in a symmetric Cournot-type payoff (C); (b) both firms defer (DD), facing an option on a symmetric Cournot-type game next period; (c) and (d) one firm invests now (I) and the other defers (D), with the first mover acting as a Stackelberg leader (S^L) acquiring a higher Cournot payoff and the follower having an option on a Stackelberg follower payoff (S^F) next period. The payoff values in each state (scenario) 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 I or Defer D) and their investment timing (simultaneous or sequential, at $t=1$ or 2).

We derive the equilibrium quantities (Q^*) and net project values or Strategic NPVs (NPV^*) for the various market structures under quantity competition and learning effects (see Complementary Appendix S1). Exogenous uncertainty in market demand is characterized by fluctuations in the demand parameter, θ_t, along the binomial tree. Following Kulatilaka and Perotti (1998), we assume linear inverse demand function:

$$P\left(Q, \theta_t\right) = \theta_t - \left(Q_A + Q_B\right). \qquad (2)$$

Demand shift parameter θ_t follows a lognormal diffusion process (or a multiplicative binomial process in discrete time). Q_A and Q_B are the quantities produced by Firms A and B, respectively, and P(Q) is the common market (industry) price as a function of total quantity ($Q = Q_A + Q_B$). Initial investment represents fixed cost, while total variable production costs depend on the size of production (Q). The total variable production cost for firm i (i = A or B) is given by:

$$C\left(Q_i\right) = c_i Q_i + {}^1\!/_2 q_i Q_i^2, \qquad (3)$$

where c_i and q_i are the linear and quadratic cost coefficients (or the fixed and variable coefficients of the marginal cost function, $c_i + q_i Q_i$) for firm i. We derive the best-response functions (reaction curves) and the equilibrium outcomes for the simultaneous Cournot (C), sequential Stackelberg leader-follower (S), and Monopoly (M) models.[10] The (gross) project value, V_i, and the net present value, NPV_i, from the second-stage investment for firm i, assuming perpetual subsequent annual operating cash flows (profits π_i) and a constant risk-adjusted discount rate (k) in the last stage, are given by:[11]

$$NPV_i = V_i - I = \frac{\pi_i}{k} - I. \qquad (4)$$

The resulting scenarios and value payoffs are described at the bottom of Figure 3 and summarized in Table 1. Firm A's strategic investment decision concerning adoption of the new over the existing technology is based on the *strategic* NPV criterion (or NPV^*) of Equation (1). This incorporates not only the direct NPV of expected incremental net cash flows (i.e., extra cost savings from adopting the new over the old technology), but also any *flexibility value* sacrifice from early commitment and the added strategic *reaction* and *preemption* values.[12]

---

[10] In a Cournot-Nash equilibrium, each firm reacts optimally to the other's expected action (based on its reaction function). The two firms simultaneously choose a pair of outputs that corresponds with the intersection of the two reaction curves. In the Stackelberg game, the two firms choose their output sequentially. Given the follower observes the leader's output selection, the Stackelberg leader chooses that output on the follower's reaction function that maximizes its own profit value.

[11] For simplicity, we assume zero taxes and depreciation so that operating cash flows are equivalent to operating profits.

[12] As noted, strategic reaction value reflects the impact of competitor's reaction on profit value via changes in equilibrium quantity for a given market structure. Strategic preemption value, more likely at intermediate demand levels, results from an abrupt change in market structure altogether, for example, switching from a Cournot-type Nash equilibrium in the base case (staying with the existing, costlier production process) to a Stackelberg leadership or monopoly equilibrium under the strategic investment alternative. More formally, the strategic effect results from the impact of Firm A's strategic investment K_A on rival Firm B's optimal second-stage quantity, dQ^*_B/dK_A, and *its* resulting indirect impact on Firm A's profit value (see Fudenberg & Tirole, 1984):

$$\frac{dV_A}{dK_A} = \frac{\partial V_A}{\partial K_A} + \frac{\partial V_A}{\partial Q_B}\frac{dQ_B^*}{dK_A}$$

(commitment value = direct effect + strategic effect)

The strategic value may be positive (e.g., if early investment creates a proprietary cost advantage and/or deters competitive entry), or negative (e.g., if it proves the market or creates shared benefits that a competitor can exploit). We refer to the incremental direct NPV (net of required investment outlay, K_A) and the total strategic value (reaction value + preemption value) resulting from

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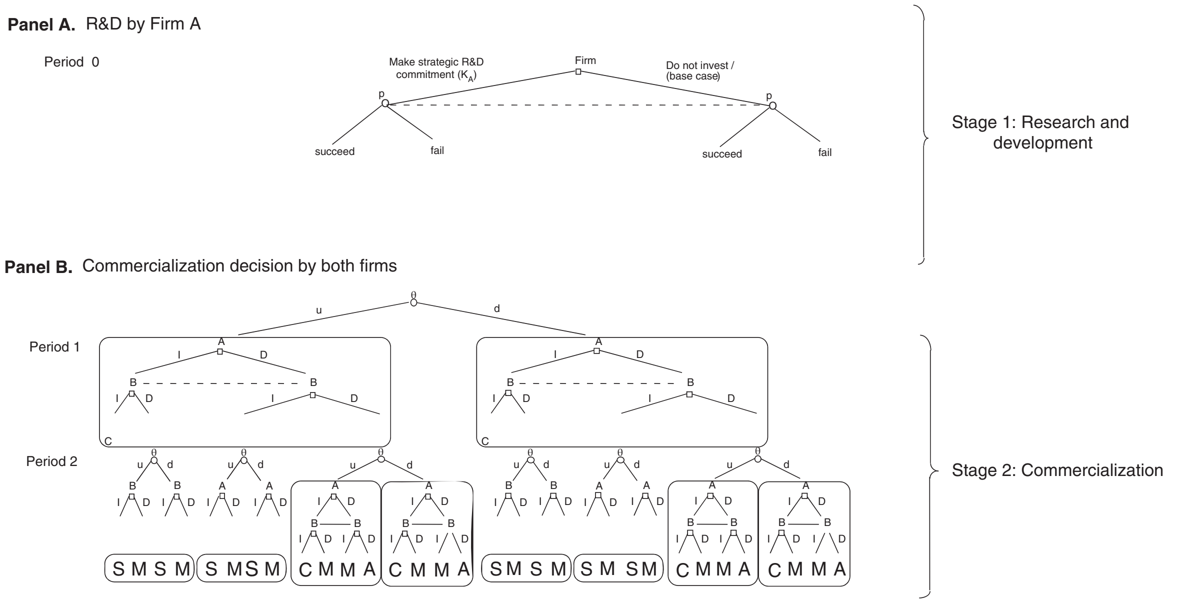

Notes. (□) represents a decision to invest (K) in R&D or defer (D) by Firm A, (○) represents technological uncertainty (chance of success).

Figure 3. The basic two-stage investment game, involving R&D and commercialization phases under different market structures.

In the numerical results that follow (summarized in Table 2), we make the following parameter assumptions. Firm A can enhance its competitive position by investing early in R&D (at a cost $K_A = 100$) that results in a more cost-efficient production process lowering its marginal cost to $c_A = 0$ ($< c_B = 5$). In the second stage, either Firm A or Firm B can invest in follow-up production capacity at $t = 1$ or $t = 2$ (costing $I = 100$) depending on demand evolution. Initial demand is $\theta_0 = 17.5$ and can move up or down with binomial multiplicative parameters $u = 1.25$ and $d = 1/u = 0.80$ (so, e.g., $\theta_1 = u\ \theta_0 = 1.25 \times 17.5 = 21.9$ or $d\ \theta_0 = 0.80 \times 17.5 = 14$). The risk-free interest rate (r) is 5% while the risk-adjusted discount rate in the last stage is $k = 13\%$. This is in the range of the typical WACC in mature industries. If Firm A chooses not to make the R&D investment (base case), the two firms would have symmetric second-stage operating costs, based on the old technology, of $c_A = c_B = 5$. In the benchmark R&D case (with no learning), the asymmetric Cournot duopoly outcome is used.

early strategic investment commitment as the *net commitment* value.

Option Games and Product Market Competition: An Illustration

To illustrate how the option games valuation works, consider the extended two-period numerical example in Figure 2. The option games valuation process starts from the end-period games (at $t = 2$) and proceeds backward. In the first step, we estimate the payoff values of the product market competition for each firm in each of the demand evolution scenarios. At time $t = 2$ in the (blown up) second subgame from the bottom at the right, we estimate the asymmetric Cournot project value (using the C formula in the upper row of Table 1) for (Invest, Invest) in the upper-left cell: $NPV_A = (17.5 - 2 \times 0 + 5)^2/(9 \times 0.13) - 100 = 333$; $NPV_B = (17.5 - 2 \times 5 + 0)^2/(9 \times 0.13) - 100 = -52$. For the diagonal cells involving (temporary) monopoly strategies ID and DI (using the M formula for the investing firm from Table 1 and 0 for the rival's expiring option at $t = 2$): $NPV_A = (17.5 - 0)^2/(4 \times 0.13) - 100 = 489$, $NPV_B = 0$; and $NPV_A = 0$, $NPV_B = (17.5 - 5)^2/(4 \times 0.13) - 100 = 200$. When both firms defer (DD), their expiring option is worthless.

After determining dominant strategies and the subgame Nash equilibrium values in Step 2 as

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Table 1
Equilibrium Quantities and Strategic NPV (NPV) for Various Market Structures*

Market structure		Equilibrium quantity under learning	Equilibrium quantity ($\gamma = 0$)	State project value ($\gamma = 0$)
Period $t = 2$				
C	Cournot	$\frac{\theta_t - 2c_A^F + c_B^F - 2c_A^L e^{-\gamma \sum Q_{At}} + c_B^L e^{-\gamma \sum Q_{Bt}}}{3}$	$\frac{(\theta_t - 2c_A + c_B)}{3}$	$\frac{(\theta_t - 2c_A + c_B)^2}{9k} - I$
M	Monopolist	$\frac{\theta_t - c_A^F - c_A^L e^{-\gamma \sum Q_{At}}}{2}$	$\frac{\theta_t - c_A}{2}$ ($Q_B = 0$)	$\frac{(\theta_t - c_A)^2}{4k} - I$
S^L	Stackelberg leader	$\frac{\theta_t - 2c_A^F + c_B^F - 2c_A^L e^{-\gamma \sum Q_{At}} + c_B^L e^{-\gamma \sum Q_{Bt}}}{3 + \frac{2}{\gamma c_B^L e^{-\gamma \sum Q_{Bt}} - 2}}$	$\frac{(\theta_t - 2c_A + c_B)}{2}$	$\frac{(\theta_t - 2c_A + c_B)^2}{8k} - I'$
S^F	Stackelberg follower	$\frac{\theta_t - c_B^F - c_B^L e^{-\gamma \sum Q_{Bt}}}{2} - \frac{\theta_t - 2c_A^F + c_B^F - 2c_A^L e^{-\gamma \sum Q_{At}} + c_B^L e^{-\gamma \sum Q_{Bt}}}{6 + \frac{4}{\gamma c_B^L e^{-\gamma \sum Q_{Bt}} - 2}}$	$\frac{(\theta_t - 3c_B + 2c_A)}{4}$	$\frac{(\theta_t - 3c_B + 2c_A)^2}{16k} - I$
A	Abandon	0	0	0
Period $t = 1$				
(II)	Cournot	$\frac{\theta_t - 2c_A^F + c_B^F - 2c_A^L e^{-\gamma \sum Q_{At}} + c_B^L e^{-\gamma \sum Q_{Bt}}}{3}$	$\frac{(\theta_t - 2c_A + c_B)}{3}$	$\frac{(\theta_t - 2c_A + c_B)^2}{9k} - I$
(ID)	Stackelberg leader (S^L)/ Monopolist(M)	$\frac{\theta_t - c_A^F - c_A^L e^{-\gamma \sum Q_{At}}}{2}$	$\frac{\theta_t - c_A}{2}$ ($Q_B = 0$)	$\frac{pV_u^* + (1-p)V_d^*}{1+r} - 1 + \frac{\pi_m}{1+k}$ [a]
(DD)	Defer	0	0	$\frac{pNPV_u^* + (1-p)NPV_d^*}{1+r}$

Notes. Profits are calculated from $\pi_A = P_A Q_A - C(Q_A)$. State project value is determined in the last stage from $NPV_A = \max(\pi_A/k - I, 0)$, where I is the required investment capacity outlay and k the risk-adjusted discount rate. (ID) means Firm A invests; Firm B defers.
[a] $\pi_m = (\theta_t - c_A)^2/4$.

discussed in the previous section (obtaining [489, 0]* for [ID] in the up subgame and [141, 0]* in the down state subgame at $t = 2$), the end-of-period payoff values are then folded back in a backward binomial tree process (see also Smit & Trigeorgis, 2004) to obtain the time-0 Strategic NPV (with an estimate of all its value components), based on the following state-contingent (option) formula (D, D, from Table 1):

$$NPV^* = \frac{p\,NPV_u^* + (1-p)\,NPV_d^*}{1+r}. \qquad (5)$$

In the above, NPV_u^* and NPV_d^* are the Nash equilibrium values in the up and down subgames, weighted by the risk-neutral probabilities in the up (p) and down demand states and discounted back to the earlier period at the riskless interest rate (r).[13] This is analogous to the basic binomial option pricing formula (e.g., see Cox, Ross, & Rubinstein, 1979), except that NPV_u^* and NPV_d^* are no longer exogenously specified payoff values in the up and down states, but rather are the equilibrium outcomes in the next-period up and down subgames optimally accounting for competitive interactions. Thus, at time $t = 1$ in the (enlarged) subgame of Figure 2, when both firms Defer in cell *iv* they obtain: $NPV_A = (0.3 \times 489 + 0.7 \times 141)/1.05 = 234$, $NPV_B = (0.3 \times 0 + 0.7 \times 0)/1.05 = 0$.

The asymmetric Cournot project values for (Invest, Invest) of (209, −86) are obtained from the (asymmetric) C formula in the upper row of Table 1. Using the formula for (ID) at period 1 (from Table 1), the value of Firm A investing at $t = 1$ (while Firm B does not invest), obtained as the discounted profit value plus net expected option value from continuing, is $NPV_A = 272$.[14] The Nash equilibrium outcome of (272, 0)* in (ID) is obtained as in Step 2 previously. Using again the backward process (of Step 3,

[13] In complete markets the risk-neutral probabilities can be obtained from: $p = [(1 + r) - (d + \delta)]/(u - d)$, where u and d represent the multiplicative up or down binomial parameters capturing up or down moves in market demand (θ), r is the risk-free rate, and δ is the constant asset (dividend-like) payout yield (equal to k/(1 + k) for a perpetual project, where k is the risk-adjusted discount rate).

[14] $NPV_A = 49/1.13 + (0.3 \times 589 + 0.7 \times 241)/1.05 - 100 = 272$; $NPV_B = 0$.

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Table 2
Value Components for R&D Investment under Different Information Structures

		Base case	Certain R&D	Learning		Technological uncertainty		Learning & techn. uncertainty	
Value component	Description	(0) no R&D	(1) R&D	(2) base case (no R&D)	(3) certain R&D	(4) complete info.	(5) prop. info.	(6) complete info.	(7) prop. info.
Net present value	(1) Investment in R&D	0	−100	0	−100	−100	−100	−100	−100
	(2) PV of cost savings	0	185	106	81	92	92	92	92
	Direct NPV		*85*						
Strategic value	(3) Strategic reaction	0	82	−43	−42	41	31	−8	−13
	(4) Strategic preemption	0	42	0	0	21	35	22	30
	Total strategic		*124*						
Flexibility value	(5) Net commitment (1 + 2 + 3 + 4)	0	209	63	−61	54	58	6	9
	(6) Flexibility value	27	0	0	0	13	10	0	0
Strategic NPV*	Strategic NPV (relative to base case, 5 + 6)		**209**	**63**	**−61**	**67**	**68**	**6**	**9**
	Base case NPV (old)	20	20						
	Total strategic NPV	47	229						

Parameters: investment: $K_A = 100$, $I_A = I_B = 100$; interest: $r = 0.05$, $k = 0.13$; demand uncertainty: $\theta = 17.5$, $\sigma = 22\%$; (0) Base case costs: $c_A = 5$, $c_B = 5$; (1). Proprietary R&D costs: $c_A = 0$, $c_B = 5$. (2) Learning: $\gamma = 10\%$; learning $c_A = 5$, $c_B = 5$ with $c_A^L = 4$, $c_B^L = 4$ and $c_A^F = 1$, $c_B^F = 1$; (3) No technological R&D uncertainty: $\eta_A = 100\%$; (4) Technological R&D uncertainty: $\eta_A = 50\%$; (5) Firm B does not know whether A's R&D succeeded or not and has an expectation of its rival's cost $E(c_A) = 2.5$. (6) Tech R&D uncertainty: $\eta_A = 50\%$ that may reduce its cost to $c_A = 0$ at success. Learning: $\gamma = 10\%$; learning $c_A = 5$, $c_B = 5$ with $c_A^L = 4$, $c_B^L = 4$ and $c_A^F = 1$, $c_B^F = 1$. (7) Firm B's expectation of its rival's cost $E(c_A) = 2.5$.

we estimate the current ($t = 0$) Strategic NPV from its respective end-of-period ($t = 1$) Nash equilibrium values: $NPV_0{}^* =$ value of Firm A's innovation option – strategic investment cost $(K_A) = [0.3 \times 517 + 0.7 \times 272]/1.05 - 100 = 329 - 100 = 229$M.

We next discuss the shape of commercialization growth option value (NPV^*) at $t = 1$ versus the state of market demand (θ) and the existence of distinct demand zones with potential discontinuities. Figure 4, Panel A confirms that the value of the strategic growth option viewed as a call option on the project is essentially a nonlinear, convex function of demand. Under rivalry, however, the outcome of the above investment subgames depends on the region of demand. In a certain region the competitive structure may change (e.g., from Cournot oligopoly to temporary monopoly) introducing value discontinuity. Given the industry equilibrium payoff values and the relative costs, the low-cost firm (Firm A) will choose to invest early, while the higher-cost rival (Firm B) will wait at intermediate demand levels. When demand is high, the market niche is sufficient for both firms to invest so the Nash equilibrium is (Invest, Invest). This is reflected in the forward (as of $t = 1$) growth option payoff value for Firm A ($NPV_A{}^*$), represented by the nondotted sections of the curves in Figure 4, Panel A. At very low and very high demand levels, clear dominant strategies emerge. In low demand, both firms defer (DD), receiving joint wait-and-see option value, whereas in high demand, both firms invest (II) with innovative low-cost Firm A capturing a greater market share due to the new technology's cost advantage (strategic reaction value). Two critical market demand thresholds, θ^*_{INVEST} and θ^*_{DEFER}, separate regime switches in three demand zones. As a consequence, the strategic growth option value is a nonlinear function of demand exhibiting some discontinuity (value jump) due to competitive preemption effects at the intermediate demand region, depending on the size of the relative innovation cost advantage.

The conditions of cost heterogeneity resulting from innovation advantage change the relative value components positioning in the option-games space of Figure 1. Figure 5 plots the flexibility value (vertical axis) versus net commitment value (horizontal) for high and low levels of cost advantage (their sum being the total Strategic NPV relative to the base case of no R&D). At low cost

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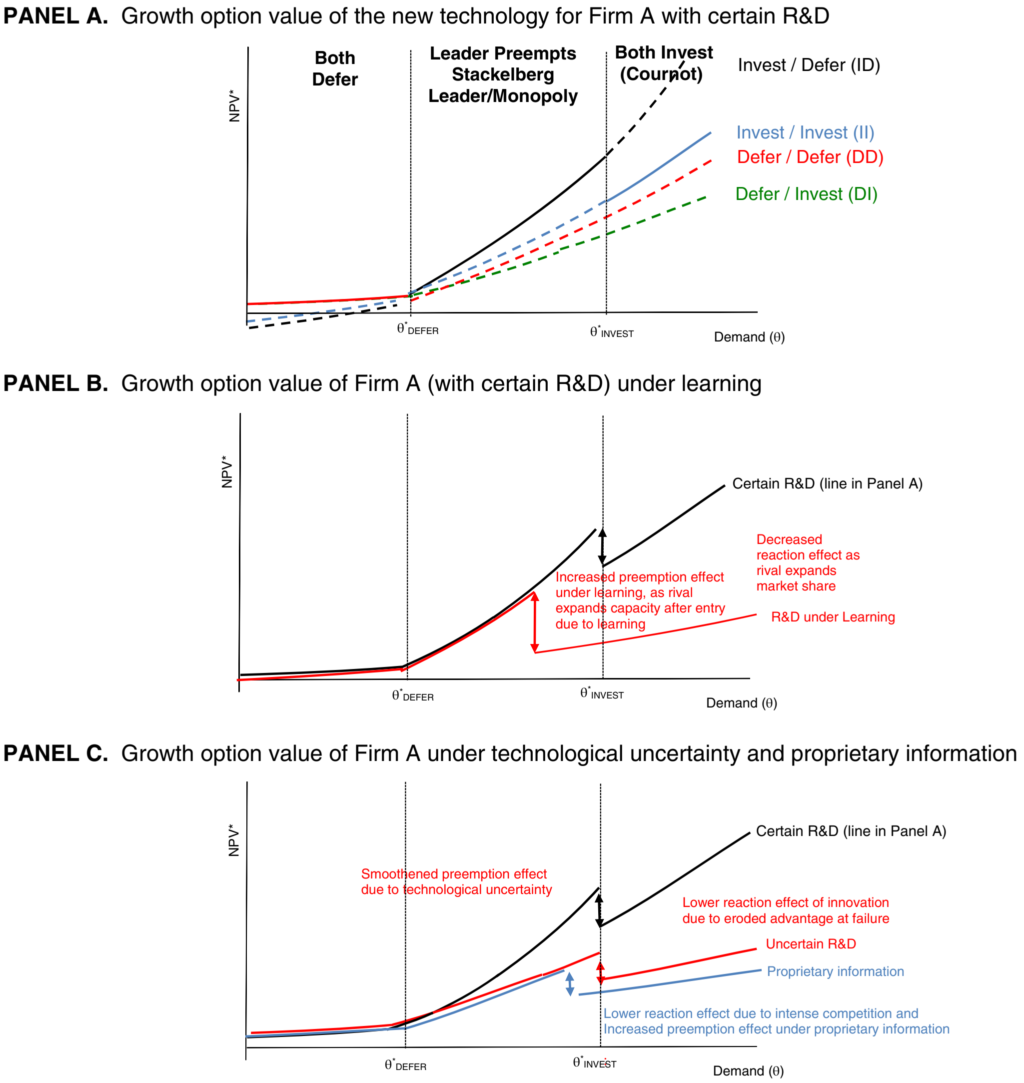

Notes.
Parameter values: Panel A: If market demand θ exceeds θ^*_{INVEST} (21.25), both firms invest (Cournot). If θ is below θ^*_{DEFER} (8.75) both defer. Investment: $I_A = I_B = 100$; interest rates: $r = 0.05$, $k = 0.13$; proprietary R&D costs: $c_A = 0$, $c_B = 5$; no technological uncertainty: $\eta_A = 100\%$; no learning: $\gamma = 0\%$. Panel B. No technological uncertainty: $\eta_A = 100\%$; learning: $\gamma = 10\%$; learning $c_A = 5$, $c_B = 5$ with $c^L_A = 4$, $c^L_B = 4$ and $c^F_A = 1$, $c^F_B = 1$. Panel C. Technological R&D uncertainty: $\eta_A = 50\%$; no learning: $\gamma = 0\%$. Proprietary information: Firm B does not know whether A's R&D succeeded or not and has an expectation of its rival's cost $E(c_A) = 2.5$.

Figure 4. Commercialization growth option value (at $t = 1$) under different information structures.

heterogeneity ($c_B - c_A < 0.8$) and small innovation advantage, there is high growth option value and real options analysis is more relevant. But in this tug-of-war, flexibility value is sacrificed (0) when the disadvantaged rival (Firm B) accepts a follower status enabling the innovator (Firm A) to enjoy a positive jump with a high cost advantage ($c_B - c_A > 0.8$), shifting the weight to strategic games due to market structure changes (strategic preemption value) or attaining a higher market share (strategic reaction value).

By way of an overview (and a roadmap of what follows), Table 2 summarizes the breakdown of total value into various components for each of the cases we examine. The base case (no R&D investment) in Column 0 (corresponding to the lower, Defer branch of staying with the old technology in Figures 2 and 3) shows the valuation based on real options of 47M (=20 + 27). Column 1 shows the Strategic NPV benchmark case of certain (with 100% success) R&D investment. Total Strategic NPV value (229) here consists of the base-case NPV

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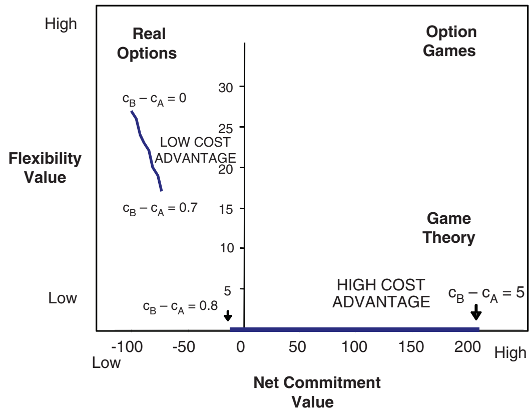

Figure 5. R&D value components in the R&D phase with degree of cost advantage ($c_B - c_A$).

of the old technology (of 20) and the net commitment value of 209 as per Equation (1). The latter net strategic commitment value (of 209) is partly due to extra combined strategic value (124) arising from the strategic reaction and preemption effects besides net cost savings (85). If Firm A invests in R&D to develop the new technology, it will gain ground over its rival in Cournot competition through a larger market share (strategic reaction value worth 82) and will also enjoy a strategic preemption advantage (of 42). These strategic benefits are in addition to the net savings from lowering future production costs of 85 under direct NPV (a direct PV of 185 in cost savings, net of the R&D outlay of $K_A = 100$). The above, summarized in Column 1 of Table 2, serves as a basis for our examination of different information structure factors, considered next.

Information Structure Conditions Driving Flexibility versus Commitment

In this section, we examine how Strategic NPV and its breakdown into calculable interacting value components can help delineate the domains where NPV, strategic games, and real options logic are most applicable under different learning, technological uncertainty, and proprietary information conditions.

Learning Experience Conditions that Tilt Decisions Toward Early Commitment

Cumulative learning experience using existing technology is an alternative (to the adoption of new technology) in reducing future production costs and so it changes the interaction among the value components and affects strategic investment decisions by rival firms. The well-known "learning curve" effect encapsulates a cost advantage from accumulated experience and know-how from production (Lieberman, 1989). Given such learning, we assume the marginal cost of Firm i ($i =$ A, B) declines exponentially with cumulative production $\sum Q_{it} (= Q_{it} + \sum Q_{it-1})$ at a learning experience rate γ, converging to a floor level c_i^F according to $c_i\left(Q_{it}\right) \equiv c_i^F + c_i^L e^{-\gamma \sum Q_{it}}$.[15]

How learning experience conditions affect the value components of the old versus the new technology choice is examined in Figure 6, Columns I and II, respectively. Column I (left) shows that the direct NPV for the old technology gets more relevant as firms achieve lower cost, but the strategic reaction effect declines as both rivals increase production (in red). As expected, when learning experience increases, firms sacrifice the option to wait resulting in a discontinuous decline in flexibility value (in light blue).[16] As a consequence, more intense learning conditions (higher γ) make producing with existing technology more attractive as cumulative costs decline (Column I, Panel B).

When higher cumulative learning experience makes an existing technology more cost-efficient, the new technology may lose strategic value. This raises the strategic preemption value of the new technology. Figure 6, Column II shows the

[15] The rate of learning experience benefits (γ), expressing how fast marginal cost declines as production accumulates, is generally firm-specific as different organizational processes embody different experiences and know-how. For simplicity and to focus on the strategic effects, we assume the two firms are similar in this respect.

[16] Flexibility value declines from 27 in the base case to 0 when the learning rate exceeds $\gamma^* = 4.5\%$. Rivals are forced to invest early (in a prisoners' dilemma game where neither firm wants to be a follower). The leader may gain an increasing advantage in industries with significant learning, for example, the manufacturing of airplanes, cars, electronics, telecommunications, and software development. Market share volume in cellular phones, for instance, might result in high preemption value (causing discontinuity and sacrificing flexibility value) when it prevents rivals from scaling up production and benefiting from learning experience. In car manufacturing, Tesla gained experience in autopilot and battery technology, challenging rivals to also invest in electric cars. However, Tesla's expanding market volume in higher volume models may also constrain rivals in catching up gaining specific learning and scale advantages in the production of electric cars. As demand volatility for electric cars remains high, car manufacturers and new rivals (such as Apple or Google/Alphabet) face discontinuities in the trade-off between waiting versus commitment due to the entry of rivals.

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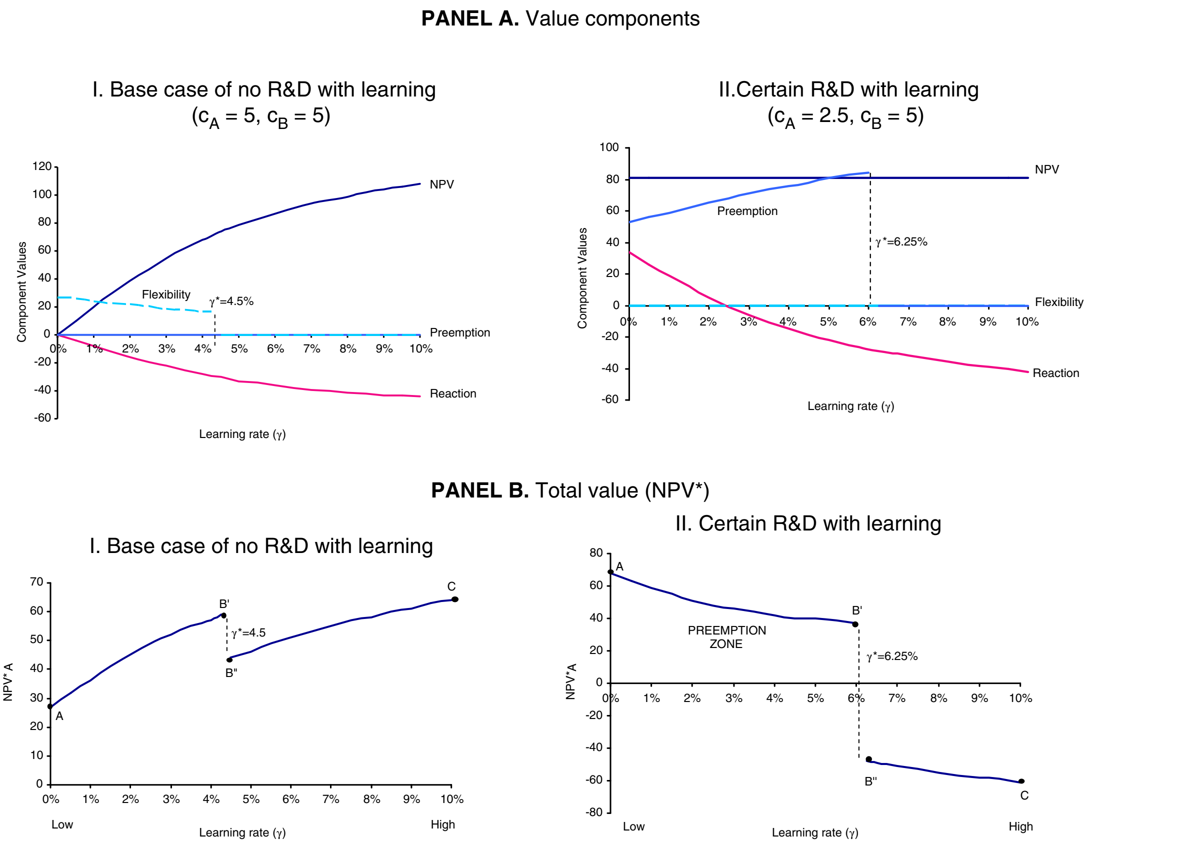

Notes. NPV* = Net commitment value + Flexibility value

A. Base Case with Learn. ($\gamma = 0\%$): 0 + 27 = 27 (Table 2 Col. 0)
B'. Base Case with Learn. ($\gamma = 4.25\%$): 42 + 17 = 59
B". Base Case with Learn. ($\gamma = 4.50\%$): 44 + 0 = 44
C. Base Case with Learn. ($\gamma = 10\%$): 63 + 0 = 63 (Table 2 Col. 2)

A. Certain R&D with Learn., c_A=2.5 ($\gamma = 0\%$): 68 + 0 = 68
B'. Certain R&D with Learn. c_A=2.5 ($\gamma = 6\%$): 37 + 0 = 37
B" Certain R&D with Learn, c_A=2.5 ($\gamma = 6.25\%$): -48 + 0 = -48
C. Certain R&D with Learn., c_A=2.5 ($\gamma = 10\%$): -61 + 0 = -61 (Table 2 Col. 3)

Parameter values: investment: K_A =100, $I_A = I_B$ = 100; interest rates: r = 0.05, k = 0.13; base demand: θ_0 = 17.5; uncertainty: u = 1.25, d = 0.8 (σ = 22%). Panel B. Proprietary R&D costs: c_A = 2.5, c_B = 5; no technological uncertainty: η_A = 100%. Initial total marginal cost c_A, c_B = 5 (= $c_A^L + c_A^F$) with a learning-cost component c_A^L= 4 c_B^L= 4, and fixed (floor) cost c_A^F = 1, c_B^F = 1 for each firm.

Figure 6. Base case value of no R&D (Column I) versus Firm A's R&D investment (Column II) with learning experience cost effects by both firms.

interacting value components of investing in the new technology (Panel A) and its total strategic NPV (Panel B). Resulting strategic value loss is evidenced in the huge value discontinuity shown in Column II in Panels A and B.[17] Panel A, Column II confirms that Firm A's preemption advantage is large under such learning experience but only attainable at low learning rates ($\gamma < 6.25\%$). Here, the high-cost rival (Firm B) experiences more learning benefits than the innovator (Firm A). Despite the high production cost savings from the new technology reflected in the direct NPV (dark blue), there is a declining strategic reaction value associated with adopting the new technology as Firm B's existing technology gets more cost-efficient through learning curve experience effects (red line). The total NPV* in Panel B shows that as the high-cost rival can no longer be preempted by the innovator's new technology investment (due to its own production learning cost advantage), there is a large downward jump in Firm A's strategic preemption value (from B′ to B″ on the medium blue line).

The breakdown of Strategic NPV (or NPV*) into value components (under certain R&D) with

[17] The context here is that new technology investment by Firm A reduces its future production costs (to $c_A = 2.5$), while production learning experience brings additional cost savings at a rate γ% to both firms.

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learning experience is summarized in Column 3 of Table 2. Column 2 benchmarks with the base case of no R&D investment (but with learning via the old technology). Besides experience cost benefits, learning can have counteracting effects on the Strategic NPV components: Although learning experience induces earlier investment by both rivals, who give up both flexibility (from 27 in base case to 0 under high learning rate, $\gamma = 10\%$) and strategic reaction value, it also induces strategic preemption effects. Under both learning experience and rivalry conditions, not only the innovator but also the rival has an incentive to invest earlier. Thus, learning experience shifts the analysis toward IO and games. A stronger learning advantage by the rival erodes direct NPV (81-106) and strategic reaction value under the new technology (-42) as the rival builds up production. Beyond a critical learning experience threshold, the strategic preemption value of the innovator gets reduced. This value gets preserved when preemption by Firm A can reduce the rival's learning advantage. If a certain technology is disruptive by making existing capacity obsolete, strategic innovation investment with preemption potential is more valuable when preemption prevents the rival from exploiting its own learning cost advantage. A lower comparative learning advantage by the rival may thus have a positive impact on the strategic reaction and preemption value of the innovator's R&D strategy as the rival cannot catch up to benefit from learning experience once it enters.

As shown earlier (Figure 4, Panel A), growth option value is a nonlinear (convex-like) function of demand exhibiting some discontinuity due to competitive preemption. As learning experience favors early investment to achieve cumulative cost benefits, learning conditions erode the flexibility value of waiting for a single firm (see also Majd & Pindyck, 1987). Under rivalry, learning experience acquires a strategic dimension due to competitive pressures as the rival enjoys learning experience benefits as well. Figure 4, Panel B shows that the growth option value under the new technology will likely result in higher preemption value discontinuities at intermediate demand levels and in negative reaction effects at higher levels of demand, making it more attractive for the innovator to invest in the new technology to preclude learning benefits by the rival. Under learning experience conditions the curve is flatter (lower) due to significant strategic preemption benefits (and large negative reaction effects) such that learning will negatively moderate the relationship between growth option value and demand.[18]

> *Proposition 1. A high learning experience increases the incentive of the innovator to invest in new technology to preempt the rival from enjoying a learning cost advantage exploiting the old technology; entry causes a downward discontinuity in the growth option value of R&D and moderates negatively the relationship between growth option value and demand.*

In terms of testable implications,[19] we expect that in industries with significant learning experience effects (e.g., shipbuilding, airplane manufacturing,[20] electronics, design and production of software) the growth option value of new technology for an innovative firm will encompass high preemption value discontinuities, providing an incentive to invest more in new technology to limit learning benefits by rivals. We expect a negative interaction term involving learning rate and demand.

Technological Uncertainty Conditions that Tilt Decisions Toward Deferring Investment

In addition to demand uncertainty, generally leading to delayed commitment decisions, there can also be technological uncertainty (Huchzermeier & Loch, 2001; Oriani & Sobrero, 2008). In this context, we use the term *technological uncertainty* broadly to refer to the (generally exogenous) probability of failure of a technological or innovation/discovery process; this pertains more to the nature and difficulty (odds) of the technological process rather than the technology itself.[21]

How varying technological uncertainty conditions affect the relative merits of flexibility

[18] The curved function in Figure 4, Panel A is similar to the convex payoff of a call option. The current option value is the discounted risk-neutral expectation of this payoff.

[19] The previous proposition may be testable since growth option value is embedded in firm market values (e.g., Tong, Reuer, & Peng, 2008) or reflected in the market-to-book ratio (e.g., Folta & O'Brien, 2004). The preemption effect is related to market entry. Folta and O'Brien (2004) defined *entry* as new activity by an existing firm in an industry in which the firm had no reported involvement in the previous 2 years. The level of demand and the learning curve effect, expressing how fast marginal cost declines as production accumulates, is typically estimated on the industry level.

[20] In airplane manufacturing, for example, Boeing and Airbus must both cope with daunting strategic preemption and reaction

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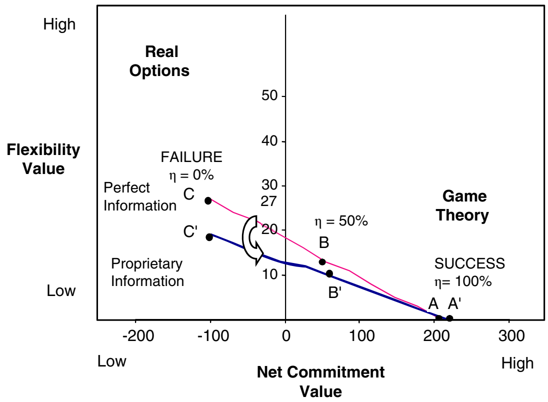

Notes. Parameter values: investment: K_A =100, I_A = I_B = 100; interest rates: r = 0.05, k = 0.13; base demand: θ_0 = 17.5 or 12.5; demand uncertainty σ = 22%: (u = 1.25, d = 0.8); no learning: $\gamma = 0$;

NPV^* = Net commitment value + Flexibility value

No Proprietary Information		Proprietary Information	
A. Certain success (η_A = 100%):	209 + 0 = 209 (Table 2 col. 1)	A'. Certain success (η_A = 100%):	217 + 0 = 217
B. Uncertain success (η_A = 50%):	54 + 13 = 67 (Table 2 col. 4)	B'. Uncertain success (η_A = 50%):	58 + 10 = 68 (Table 2 col. 5)
C. Certain failure (η_A = 0%):	-100 + 27 = -73	C'. Certain failure (η_A = 0%):	-100 + 19 = -81

Figure 7. Strategic NPV (NPV^*_A) with technological R&D uncertainty and proprietary information.

versus commitment on the Strategic NPV of R&D investment is shown (by the upper line) in the option-games space of Figure 7. A limited probability of Firm A's R&D success (η_A) changes its expected cost $E(c_A)$ and future production capacity, and thereby, its strategic growth options. The expected value of Firm A's R&D investment varies linearly (from point A to B to C) with its probability of R&D success (η_A from 100 to 50 to 0%). Conditions of technological uncertainty thus cause interacting shifts in the flexibility-commitment trade-off, critically impacting on the timing and value of the investment decision. While the net commitment value of R&D declines (from 209 at point A, to 54 at B and -100 at C) with a lower probability of R&D success, flexibility value increases but to a lesser degree (from 0 to 13 to 27). Table 2, Columns 1 and 4 confirm that, in net, Strategic NPV declines (from 209 to 67) with $\eta_A = 50\%$.

Varying its level alone, while holding the expected R&D cost reduction constant (a mean preserving spread), technological R&D uncertainty is seen to mitigate the strategic preemption benefit (less discontinuity). If successful in its R&D, Firm A will preempt the rival with a drastic cost advantage (of $c_A = 0$ vs. $c_B = 5$), while if it fails it cannot preempt (hence, no jump). In first-stage R&D growth option value, technological uncertainty will mitigate market preemption effects compared to R&D investment with a certain cost reduction. Value discontinuity due to preemption manifests itself toward the end of the staged R&D process when technological uncertainty is resolved and the balancing impact goes away.

The red curve in Figure 4, Panel C shows that technological uncertainty (when interacting with demand and competitive uncertainties) shifts the balance toward waiting as the probability

effects as they face duopolistic competition, uncertain demand, and cumulative learning effects.

[21] Strictly speaking, by *technological uncertainty*, we refer to the concrete probability $(1-\eta)$ that the R&D effort to develop a new technological process may fail (implying a limited probability of R&D success, η). For simplicity, we treat this as mostly being exogenous (given). Some of the readers may be more familiar with the definition in Pindyck (1993) concerning uncertainty related to the cost to completion in developing the new technology or product. In other contexts, technological uncertainty may be partially endogenous as it might be resolved through more investment (e.g., Roberts & Weitzman, 1981; Tushman & Rosenkopf, 1992; McGrath, 1997; Huchzermeier & Loch, 2001). The probability of success (or failure) may be a function of the technology used, but here we simplify by assuming that given the technology under consideration there is a specified probability of failure. Related to this, Bettis (1983) noted that although the risk associated with cash flows on completion and commercial launching involves a systematic risk component, purely technological risks during early R&D stages are typically idiosyncratic. Technological uncertainty may further result in additional value if there are switch options to alternative technologies (Oriani & Sobrero, 2008).

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of R&D failure lowers early R&D commitment value. Early-stage technological uncertainty offsets later-stage demand and competitive uncertainties (driving preemption discontinuities and reaction effects), and thus, lowers the growth option value compared to the base case of certain R&D (black curve in Panel C). As a result, strategic preemption advantages in the product market will be more pronounced during later commercial operations, while their impact will be mitigated during the early R&D stages.

> *Proposition 2. High technological uncertainty associated with a high probability of R&D failure mitigates the strategic preemption discontinuity effects due to market and competitive uncertainty in the product market, and thereby, moderates negatively the relationship between growth value and demand.*

It has been known that technological uncertainty can jeopardize firms' decisions beyond market uncertainty (Anderson & Tushman, 2001) and may erode future growth option value (Oriani & Sobrero, 2008). However, in the interplay among technological uncertainty, competitive rivalry, and market uncertainty, technological uncertainty arising from the risk of failure in early stages acts to balance out opposing effects caused by demand uncertainty under rivalry conditions, mitigating the nonmonotonic impact of market uncertainty as a result of rival preemption. We expect that in industries with high technological uncertainty manifested in a significant probability of failure, such as mining exploration that may fail to result in exploitable minerals or pharmaceutical R&D with drug discovery or safety failure rates, later-stage preemption discontinuities associated with demand or rivalry uncertainty conditions will be dampened in early technological discovery stages. Empirical correlates for technological uncertainty are often based on in-depth history of specific industries (e.g., Tushman & Anderson, 1986). Oriani and Sobrero (2008) measured technological uncertainty based on patent data indicators having validity across different industry groups.

Proprietary Information Tilts Decisions toward Immediate Investment: Back to NPV?

If there is ambiguity about the R&D success or cost structure of the innovator, a rival may base its beliefs driving its output and capacity decisions on its expectation of the innovator's cost (than on actual figures).[22] This may bias investment scale, timing, and the intensity of competition, and thus, the breakdown of Strategic NPV components.

The direction of change in the value components clearly depends on the resolution of R&D uncertainty. Points A, B, and C on the thin line in Figure 7 represent the situation where rival Firm B knows the innovator's cost structure. The rotated solid line below it shows how conditions of proprietary information and ambiguity about the innovator's costs change the Strategic NPV of investing in the new technology (points A′, B′, C′).[23] In case R&D succeeds (point A), the value of Firm A's growth option is lower due to intensified product market rivalry arising from Firm B's misestimation of A's cost. Proprietary or ambiguous information conditions lead rival Firm B to overestimate the innovator's actual cost in its growth option exercise decision (using the higher average or expected cost), producing a higher output, and thus, hurting the innovator's profit and value. While it is known that proprietary information may cause overinvestment and a lower strategic reaction effect, we show here that strategic preemption value may also increase in an offsetting manner. In preempting its rival, Firm A can avoid intensified rivalry damage from B's misestimation, and thus, attains a higher value (A′ vs. A).

Opposite interactions involving proprietary information conditions on the growth option exercise decision of the rival occur in case of Firm A's R&D failure (point C). As the rival sets a lower quantity, proprietary information conditions now cause

[22] The innovator firm typically has proprietary information about its own R&D success so the valuation and exercise of its own strategic growth option is based on its actual cost figures. However, as the rival is ambiguous about Firm A's actual costs it uses the expectation of the innovator's cost in the exercise of its own growth option. Since Firm A's expected quantity is linear in A's expected cost, the Cournot equilibrium values are equivalently obtained by using Firm B's perceived *expected* cost of Firm A. For instance, if Firm B has no information whatsoever whether Firm A's effort succeeds or not (using $\eta_A = 50\%$), Firm B's estimation of A's cost will be $E_B\ (c_A) = 0.5(5) + 0.5(0) = 2.5$. Firm B now faces a stochastic reaction function maximizing its expectation of profit values over Firm A's being a low-cost or high-cost type, contingent on Firm A's success or failure.

[23] In case of sequential investment, Firm A's private information is revealed over time when the innovator exhibits the behavior of a successful (or failing) innovator. In a Bayesian (separating) equilibrium, Firm B can observe the innovator's quantity choice in the prior period and can infer whether the innovator is a low-cost or a high-cost type. The incentive compatibility conditions that Firm A will not set a misleading quantity are satisfied.

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positive strategic reaction effects with a beneficial influence on the Strategic NPV of Firm A's R&D investment ($NPV^*{}_A$). However, flexibility value also declines (C′ drops below C) because the higher value induces the innovator (Firm A) to invest early. As a result, the line "rotation" may be opposite from what one would expect from the strategic reaction effect alone. These opposite valuation biases (i.e., the value loss due to Firm B's overestimation of Firm A's cost under R&D success and the value gain due to the opposite misestimation in case of R&D failure) roughly offset each other in determining the current expected value of Firm A's R&D with $\eta_A = 50\%$ (middle-point NPV^* at B′ = 68 vs. 67 at B). In general, the above effects are more pronounced at medium demand under high volatility and high relative cost advantage from innovation.

The breakdown of interacting value components under complete versus proprietary information is shown in Columns 4 and 5 in Table 2. We can summarize the above insights as follows. Proprietary information regarding R&D success (in interaction with technological, demand, and competitive uncertainty) balances out opposite misestimation biases in the rival's responses in case of R&D success versus failure. Figure 4, Panel C shows that proprietary information (blue line) tends to lower the growth option value compared to technological uncertainty (red) and certain R&D (black). This shifts strategic analysis from options and games back toward NPV. Under proprietary information, there are several counteracting effects on strategic value components (comparing Columns 4 and 5 in Table 2): (a) flexibility value declines (10 vs. 13) as lessened competition (rival underinvestment) in case of R&D failure induces earlier innovation by Firm A; (b) strategic reaction value is reduced (31 vs. 41) as the rival overinvests in case of R&D success, with the opposite in failure; (c) strategic preemption is more valuable (35 vs. 21) as it can avoid competition in success—though less so in failure.

Proposition 3. Proprietary information and ambiguity concerning the success of the innovator's R&D has offsetting effects on strategic value components due to rival misestimation biases in case of R&D success or failure, and moderates negatively the relation between growth value and demand.

It is known that by adjusting its strategy, an incumbent can influence a rival's beliefs about the market potential (Turut & Ofek, 2012). Production costs in an industry are not easy to infer when production technology is proprietary and is difficult to ascertain or when intellectual property rights effectively deter rival imitation (Gilbert & Newbery, 1982). We here highlight that in a competitive context proprietary information concerning the success or failure of a rival's R&D efforts biases the rival's production and investment decisions, thereby affecting the flexibility and strategic value components and tilting the analysis back toward NPV.[24] Our above analysis is in line with related strategy and IO literature that has shown that an incumbent can secure an advantage by keeping new information (about demand or technology) proprietary (e.g., McGahan, 1993), but we further show how this insight can explicitly help address the trade-off between flexibility and commitment.

Two-factor Interaction Effects

Table 2, Columns 2–5 show how information structure factors such as learning experience can affect different components of value differently than technological uncertainty or proprietary (incomplete) information. How significant, in terms of magnitude or economic importance are, however, the interactive effects of two such factors, acting concurrently, on firm value? More fundamentally, would the concurrent presence of two factors amplify and reinforce each other (positive interaction) or would they dampen each other due to inherent conflict or mutual exclusivity conditions so that the whole is less than the sum of separate parts? (Trigeorgis, 1993b; Makadok, 2010).

The last two columns of Table 2 illustrate the effect of interaction on firm value between learning experience and technological uncertainty (Column 6), and their further interaction with proprietary

[24] In a traditional NPV calculation, managers base their investment (and policy) decisions on *expectation*s of operational cash flows based on (averaging) future scenarios of market (e.g., demand) uncertainty. When rivals cannot readily ascertain the other's future production costs or when there is additional uncertainty about rival characteristics or behavior, a firm's volume and timing decisions (or policy "zones"), and particularly, its decision whether to preempt a rival or wait are out of necessity based on (misplaced) expectations. This is quite general as in many innovative markets production costs are hard to assess, for example, Tesla keeps the cost for car batteries proprietary. As it is more difficult to establish if events turn out the same or differently than expected, both managerial flexibility to adjust and commitment value are more difficult to realize.

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information (Column 7). To understand the interactive effect between learning and technological uncertainty involving a probability of R&D failure, note that in case of failure, cost savings can alternatively be achieved via learning-cost experience effects by expanding production with the existing technology. However, these learning experience benefits from enhanced exploitation of the existing technology are not fully achievable in case of technological R&D success for Firm A as in that case cost reduction is more effectively achieved via investment in the new technology. Since successful R&D innovation and learning experience cost effects from higher cumulative production based on existing technology are alternative pathways to achieve desired cost savings, and since in case R&D succeeds, they, in effect, become mutually exclusive, undertaking both initiatives concurrently (the interactive effect) will be much less beneficial than what the sum of the separate initiatives would attain:

> *Proposition 4. The joint effect of learning experience and technological uncertainty will be less than the sum of the two separate effects due to mutual exclusivity in case of R&D success, resulting in a strong negative interaction.*

The interactive value of both effects jointly is estimated as the (strategic) value of the project with both of these features versus the value of the project without them. In Table 2, total Strategic NPV is much less (6) under the interactive scenario shown in Column 6, than in the base case of a separate learning initiative without R&D (63) shown in Column 2 or in the case of a separate R&D investment involving technological uncertainty without learning under complete information (67) shown in Column 4.[25]

The additional presence of proprietary information (Column 7) amplifies both the negative strategic reaction effect (from −8 to −13) as well as the positive preemption effect involving a switch among industry structures (from 22 to 30). That is because, in this case, information on Firm A's potential R&D success and resulting lower costs is proprietary to Firm A and unknown to Firm B who, as a result of misestimation of its rival's cost (using the higher average cost), pursues comparatively larger production and enjoys higher learning experience benefits from existing technology despite Firm A's innovative R&D success. As a consequence, it becomes more valuable when Firm A can preempt its rival and avoid this misguided rivalry. The learning and technological uncertainty effects are no longer mutually exclusive. The resulting offsetting net influences on strategic reaction and strategic preemption effects increase strategic NPV only marginally in this case (from 6 to 9).

The above negative interaction effects among two information structure factors arising from effective mutual exclusivity are analogous to the less-than-sum-of-parts effect of Makadok (2010) due to the logical implausibility of managers trying to simultaneously preclude the competition (rivalry restraint), while also trying to win it (competitive advantage). Although in our context it is not a managerial choice to try to pull both levers simultaneously when it does not make economic sense, it is still important to intuitively understand the conditions that may lead to such highly interactive situations, particularly when learning experience interacts with other information structure factors. These interactions are of critical import in tilting the balance between strategic commitment and flexibility forces and assessing whether overall Strategic NPV indeed leads to value creation and capture.

Discussion, Implications, and Research Directions

In discussing implications for future theory development, Makadok (2010) envisioned two other key factors for any general theory, besides rivalry restraint and competitive advantage: information asymmetry and commitment-timing flexibility. This article takes a step toward integrating these two new factors. There is an inherent trade-off between commitment and flexibility as there are two conflicting levers (games) that must be managed concurrently: one against nature (the focus of real options, optimizing against uncertain

[25] The lower interactive value is a result of several subcomponent effects: (a) an R&D investment with technological uncertainty does not benefit from the additional direct cost savings arising in a learning experience context; (b) the net commitment effect of R&D is lower compared to the case without learning experience (6 vs. 54), mostly due to a reduced reaction effect as the rival increases production. This effect is limited under uncertainty as Firm A can also utilize learning experience advantages in case of failure of its R&D effort; (c) increased rivalry due to learning experience effects erodes the flexibility value present in the case without learning experience.

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demand), and another against rivals (game theory). Commitment can give a firm an advantage in the game against rivals by influencing their behavior, for example via preemption (endogenous strategic uncertainty), but a disadvantage against nature when there is genuine exogenous market uncertainty. Flexibility gives an advantage against nature but disadvantage against rivals. When the firm faces learning experience effects and information asymmetry conditions in addition, interaction effects make the trade-off more challenging. The construct of Strategic NPV can help strategy researchers and managers with how they should consistently quantify the various components and interactions of their investment decisions. We next discuss its relation to existing theories, boundary conditions, empirical implications, and future research.

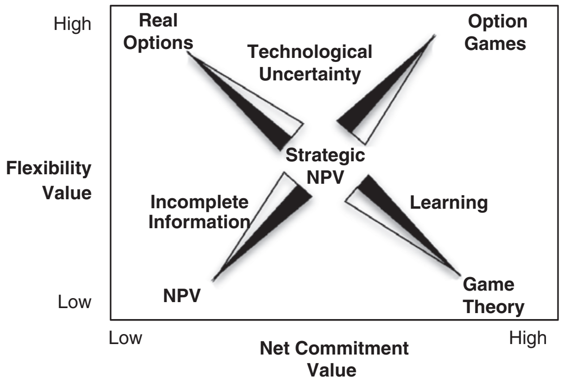

Figure 8. Relevant theories and value components in option-games space under different information structures.

Relation to Management Theories

Extant management theories focus on different sources of value (or costs), but are not explicit about which valuation framework they rely on. Strategic management theories explain how complementary organizational assets, unique resources, and adaptive capabilities lead to inter-firm asymmetries driving differences in option exercise and timing behavior, such as first-mover or follower entry. NPV is adequate when the investment context is predictable. Under conditions of rivalry and uncertainty, however, Strategic NPV can better express the full sources of value creation and capture and quantify the way the value components interact. Since a firm's history of resource accumulation, experience learning effects and capability development may differ from its rivals, firm value components will depend not only on the level and volatility of own demand and future growth option value drivers, but also on the capabilities, value drivers, learning experience, and information set of rivals. Strategic NPV is thus essential to accurately portray and operationalize strategic decisions underlying alternative management theories depending on information structure.

Uncertainty is at the root of the tug-of-war between commitment and flexibility. As a result, important differences arise between Strategic NPV and existing management theories due to their different focus on expected plans, costs, and cash flows, and the different treatment of uncertainty, be it exogenous (market demand) or endogenous (competition). Consequently, they differ in terms of their focus on cost efficiency or value creation, the role of information, of experience learning, and decision flexibility. Strategic NPV draws on these factors in an integrative way, and hence, carries considerable integration potential with other theories. Our Strategic NPV analysis thus has the potential to help integrate aspects of several management theories with high cross-disciplinary theory building potential. For example, another type of game that the focal firm could play is with actual or potential collaborators, such as input suppliers or users of its products or services. The current article does not deal with such firm boundary issues, but future work could fruitfully focus on this type of extension.

Delineating Boundary Conditions

We utilized option games as part of an integrative Strategic NPV framework to calculate value components, estimate interactions, and identify conditions when NPV, real options, or strategic games play a more relevant role in strategy decision making. Figure 8 summarizes the potential of Strategic NPV as a "compass" for strategy valuation and decision making. The nontrivial interactions among cash flows (NPV), flexibility value (real options), and commitment value (game theory) components set the industry context and delineate the boundary conditions whereby NPV, real options, or games are more or less relevant under different information structures.

Guided by this compass, we obtained several propositions reexamining the flexibility versus commitment tug-of-war in a new light. Several new insights arose. First, although learning

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experience might offset flexibility value, there is a strategic preemption benefit when preempting the rival eliminates its learning advantage. The context of learning under rivalry thus places greater emphasis on commitment and preemption (game theory). Second, technological uncertainty due to probability of R&D failure mitigates preemption value discontinuities, deemphasizing game theory in favor of flexibility (real options). When technological success is more certain, preemption advantages in the product market get mitigated, increasing the role of real options theory. Third, proprietary information mitigates the above preemption effect of R&D, shifting the emphasis from options and games back to NPV. Thus, besides extending the application boundaries of NPV and real options to capture competitive interactions and strategic effects with nonmonotonic impacts, Strategic NPV also helps provide managerial guidance on the conditions different information structures lend more weight to one or another management theory, helping address relevant model uncertainty.

Research Directions and Empirical Implications

Our study raises a number of theoretical and empirical issues that may be addressed in future research. One key issue is: How can future research more effectively separate out Strategic NPV's predictions from those of alternative theories? Although our analysis was simplified, our results do not depend critically on the functional form used for the demand or cost assumptions. It is up to empirical testing to verify the propositions and insights developed herein. Some may be testable since the flexibility and commitment values are embedded in stock prices. The growth option value can be inferred from market values such as market-to-book ratios (e.g., Folta & O'Brien, 2004; Tong et al., 2008) and can be related to product market characteristics, such as learning experience, technological failure, and the level of proprietary information. These implications might be tested against firm behavior using data on rivals' relative market performance. Our analysis suggests that strategic preemption due to firm heterogeneity causes value discontinuities and enhanced asymmetry in growth stock value. These discontinuities are moderated by the degree of innovation advantage, technological uncertainty, proprietary information, and by learning effects relative to rivals. In industries with learning experience effects, new technologies will bring about high preemption value discontinuities and overinvesting incentives to limit learning benefits by rivals. Learning cost effects should diminish the strategic preemption effect of R&D in predictable ways. In industries with high technological failure, such as in pharmaceutical R&D, later-stage preemption discontinuities will be dampened in the early stages. We anticipate that high technological failure will interact with commitment so that strategic preemption will more fully manifest itself during commercial operations, while the effect would be milder during early R&D stages. Growth option value in industries with high technological uncertainty may thus not fully manifest the disruptive strategic effects following the R&D phase. They may also differ in time-value dynamics from stable industries. Proprietary information should negatively moderate the above relations. Finally, hypothesized interactions between factors (e.g., learning and technological uncertainty) and moderating effects can be tested. Near mutual exclusivity between learning benefits and technological uncertainty would significantly diminish their joint effects. We encourage follow-up research to empirically test these implications to help better explain actual innovative firm behavior and market value dynamics.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Appendix S1. Cournot and Stackelberg equilibria with learning.

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