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Introduction of New Technologies to Competing Industrial Customers

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Motivated by several examples from industry, such as the introduction of a biotechnology-based process innovation in nylon manufacturing, we consider a technology provider that develops and introduces innovations to a market of industrial customers—original equipment manufacturers (OEMs). The technology employed by these OEMs determines the performance quality of the end product they manufacture, which in turn forms the basis of competition among them. Within this context of downstream competition, we examine the technology provider's introduction strategies when improving technologies are introduced sequentially.

We develop a two-period game-theoretic framework to account for the strategic considerations of the parties involved (i.e., the technology provider and the OEMs). Our main result indicates that the technology provider may find it beneficial to induce partial adoption of the new technology, depending on the technological progress the provider intends to offer in the future. We analyze many technology-specific and market-related characteristics—such as volume-based pricing for new component technologies, upgrade prices, and OEMs with differing capabilities—that correspond to various business settings. Our key result (i.e., partial adoption) proves to be a robust phenomenon. We also develop additional insights regarding the interactions between adoption and OEM capabilities.

Key words: technology introduction; technology adoption; game theory; industrial markets; industrial customers; business-to-business; multistage game
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1. Introduction

It is often the case in business-to-business (B2B) markets that technology providers introduce and sell new process and component technologies to firms that compete for the same downstream end-product market. These technology providers, on the other hand, usually operate in monopoly or near-monopoly positions.

We offer the following motivating examples from two industries: In chemicals, DuPont recently developed a new biotechnology-based process, namely, Sorona GT, which produces a nylon-like polymer out of corn starch using a genetically engineered version of a common bacterium (Miller 2002; *Wall Street Journal* 2003, 2004). This new process exhibits significant advantages to the adopters in terms of both cost effectiveness and end-product properties of the manufactured polymer. Consequently, DuPont has announced the sale of its textiles division (including nylon) and has established a new division to exploit the benefits from "selling" the Sorona GT process and their future innovations (*Forbes Magazine* 2003, *Wall Street Journal* 2003).

In electronics, a relatively medium-size firm, Advanced RISC Machines (ARM), is the market leader in developing and selling architectures for cell phone handset manufacturers. Although ARM is a near monopolist, with upward of 80% market share, its customers—Nokia, Motorola, Siemens, and Samsung—have significantly less market power and compete intensely in various segments of the cell phone handset market.

These examples describe a business context that is the focus of this paper. Near-monopolistic technology providers develop new process technologies or architecture/component technologies based on patented intellectual property (IP) and introduce these technologies to markets of competing industrial customers (hereafter referred to as OEMs or simply as customers).

The process or component technologies utilized by an OEM influence the performance of the end product it manufactures (e.g., nylon, textiles, or cell phones).

The performance of these end products, in most contexts, determines the end-customer choice and thus affects an OEM's market share and revenue. Hence, the performance quality of end products (which is determined by the technologies utilized) forms the basis of competition among the OEMs. Quoting a Motorola manager (an ARM customer): "[ARM's architectural solution] benefits the licensees in providing time to market, design, and customizing features" (*RCR Wireless News* 2003). Furthermore, past research has found empirical support for the impact of core components and technologies on product competitiveness (Schilling 2000) and on the evolution of industries (Tushman and Murmann 1998, Baldwin and Clark 1999).

Within this context of strategic technology introduction and competitive adoption, we develop an analytical model that explores the determinants of the technology provider's introduction decisions. First, we derive and analyze the optimal technology development and pricing decisions of a monopolistic technology provider that introduces new technologies to a market of OEMs with similar integration capabilities. We discuss two distinct scenarios: (a) technology providers that have committed to a technology road map and decide on pricing in every introduction, and (b) technology providers that employ both levers—pricing and development—and may decide on both. Next, we extend the base-case model to more general technology markets by explicitly considering the nature of the technology and the constraints it imposes (e.g., significant installation/integration costs, potential for upgrade prices, or volume-based pricing in the context of new component technologies) and the OEM market-related attributes (such as the capability differences among OEMs). We employ a two-period game-theoretic framework to capture the dynamics of technology introduction strategies.

Our results indicate that the technology provider (provider, hereafter) may find it optimal to induce partial adoption of the new technology through the appropriate pricing decisions. This result is robust across different scenarios, even in the case where all OEMs initially employ the same technology. Under this "partial adoption" strategy, the provider induces the nonadopters of currently offered technology to adopt future technological offerings. Because a part of the OEM market (is induced to) pass over one technology to adopt the future technology, we call it the "leapfrogging" strategy. The optimality of this strategy depends on the magnitude of the technological progress or, equivalently, on the development cost structure. We establish a technology progress (development cost) threshold, above (below) which the leapfrogging strategy is no longer optimal, and the provider optimally induces all the OEMs to adopt ("saturation" strategy).

We also explore the effect of some key parameters on the optimal policy. We find that even for negligible development costs, offering a superior technology may lead to lower revenues for the provider. Lower probability of delayed technology introduction results in the technology provider undertaking lower development effort. Finally, provider revenues (and profits) are shown to be convex and decreasing in the probability of delayed launch, offering additional theoretical support for the importance of reliability and time-to-market in technology development (Hendricks and Singhal 1997).

Our extensions, in addition to illustrating the robustness of the base-case results, also allow us to develop insights regarding the technology introduction decisions when the OEMs have heterogeneous technology exploitation capabilities. We categorize these capabilities based on the mechanism by which they enhance the OEM's end-product quality, enabling us to identify that the technology provider should optimally focus on (i) OEMs that have superior (greater) capabilities, if these capabilities enhance the value of the employed technology (e.g., new product-development capabilities), and (ii) on OEMs that have inferior (lower) capabilities, if these capabilities provide value independently of the technology (e.g., supply chain efficiency or logistics capabilities).

This paper makes several contributions: On the theoretical side, we offer a comprehensive game-theoretic framework that accounts for the interactions between the technology introduction decisions and the technology adoption decision. Previous normative academic literature has focused on only one of those two aspects. Several examples from B2B markets, however, indicate a strong linkage between the two, suggesting the need for a more holistic approach. On the applied side, we discuss how our findings can be translated into managerial guidelines. As with most abstract mathematical models of high-level strategic phenomena, our model is not meant to be applied as a decision-support tool, as any real situation contains numerous confounding factors. Still, the sensitivity results may be cautiously used to build intuition regarding the directional impact of interactions between relevant measurable variables, such as the performance improvement offered by future innovation, the development uncertainty, and the market growth.

The rest of this paper is organized as follows: In §2, we give a brief review of the operations management, marketing, and economics literature relating to technology adoption and new product introduction. The model is introduced in §3. The analysis of the base-case model is presented in §4. Section 5 presents various extensions to the base-case model. Finally, §6 concludes with the managerial implications, limitations of the model, and some future research directions.

2. Literature Review

There are three areas in the academic literature that have explored different issues related to our research question: first, the technology adoption literature, which has analyzed the strategic adoption decision of firms assuming that both technology and prices are exogenous variables; second, the new product introduction literature, which has examined questions relating to the timing and/or the order of introduction of durable new products; and third, the intertemporal price discrimination literature, which has studied how firms selling to heterogeneous markets modify prices over time to extract maximum revenues.

2.1. Technology Adoption

Competition among firms and its effect on adoption times have been studied in a wide variety of contexts. Balcer and Lippman (1984) study the effect of performance expectations of future technologies on adoption time and prove the existence of an optimal threshold level for the difference between best technology in the market and the firm's current technology, below which adoption does not occur. Also, they claim that this optimal threshold increases when the discovery potential is higher (i.e., technology improves more rapidly). Subsequently, Kornish (1999) showed that this sensitivity result is incorrect. Reinganum (1981a, b) examines a continuous-time formulation of competitive technology adoption and concludes that there exists a "diffusion equilibrium" even if the adopting firms are ex ante identical. This diffusion effect occurs because once a firm commits credibly to adoption at a certain time, its competitor would find it beneficial to adopt later, after the cost of technology has sufficiently decreased. The validity of this result is disputed by Fudenberg and Tirole (1985), who demonstrate that the diffusion equilibrium in Reinganum's continuous-time game is not subgame perfect and hence not credible.

Jensen (1982) considers the competitive adoption of an exogenously arriving technology and identifies the technology uncertainty (both in timing as well as in magnitude) as an explanation for the empirically observed diffusion patterns. McCardle (1985) builds on this work and develops a single firm model of technology adoption in which delaying the adoption decision can be accompanied by information collection to reduce the associated uncertainty. Because information acquisition is costly, even in optimal behavior, unprofitable technologies may be adopted. The model is extended by Mamer and McCardle (1987) to include competition and market uncertainty regarding competitors' adoption decisions. Product substitutability is shown to make adoption less likely. Gaimon (1989) considers the competitive adoption of exogenously arriving cost-reducing process technologies alongside the scrapping of old technologies. She distinguishes between open-loop and closed-loop strategies and finds that the ability to commit credibly to adoption decisions results in greater profits and greater extent of technology adoption.

2.2. New Product Introduction

Moorthy and Png (1992) explore the effect of customer expectations and impatience on the introduction strategies for two durable products. They conclude that sequential introduction is preferable to simultaneous introduction when cannibalization is significant and consumers are more impatient than the seller. Cohen et al. (1996) explore the effects of competition on the launch dates and the performance of new products. A firm facing more intense competition should aim either for greater product performance or for earlier product launch.

Dhebar (1994) considers a monopolist selling a durable product to a heterogeneous downstream market and analyzes the impact of future improved versions on the price of current technology. He shows that without credible commitment on the future prices and the future quality, no equilibrium strategies exist. Kornish (2001) extends his work, assuming that the firm is capable of (credibly) not offering upgrade prices; she shows that this may result in a credible (subgame perfect) equilibrium pricing strategy. In this paper, as one of the extensions, we consider rational and competing industrial customers and show that even with upgrade prices, there exists a subgame perfect equilibrium pricing strategy. On the product design and development side, Krishnan and Ramachandran (2006) analyze a monopolist selling design-intensive products to rational customers. They find that architectural decisions (specifically, decisions to split a product into modules) can reduce consumer regret and enable the monopolist to maintain a credible price-discrimination strategy.

2.3. Inter-Temporal Price Discrimination

Coase (1972) explores the intertemporal price discrimination behavior of a durable-goods monopolist and finds that, assuming rational and patient customers and infinitely durable goods, the price must instantly fall to the marginal cost. Although the original Coase model was formulated in continuous time, identical effects (i.e., loss of monopoly power) have been observed even in the discrete period settings (Bulow 1982). The validity of the Coase result and its assumptions (under the name *Coase conjecture*) has subsequently come under close scrutiny (Bagnoli et al. 1989, Guth and Ritzberger 1998). A set of sufficient conditions—for example, finite collection of customers, finite capacity supplier, increasing marginal cost of production—has been identified under which the Coase conjecture fails to hold. For a thorough discussion of price discrimination mechanisms, see Varian (1989).

All three streams of literature discussed above focus either on new product introduction to nonstrategic customers or on technology adoption decisions made by competing firms under exogenously determined adoption costs. In this paper, we model and analyze the effects of downstream competition (among the OEMs) on the technology provider's new technology introduction. We identify the technology demand as endogenous by establishing the link between the technology adoption decisions and the technology introduction strategy. Finally, we account for the strategic considerations of the industrial customers and analyze the resulting (multiple) subgame perfect Nash equilibria to derive the optimal technology introduction strategy.

3. Model Setup

Consider a monopolist technology provider that develops and sequentially introduces new product/process technologies to a market of n competing OEMs. We focus on a two-period model to capture the dynamic intertemporal effects, a standard assumption in related literature (Dhebar 1994, Kornish 2001). Period 1 accounts for the current technology introduction and development of a new technology, whereas Period 2 accounts for future introduction.

The technology provider "prices" a new technology[1] T at $\mathbf{W}_1$ and introduces it into a market of competing OEMs in Period 1. The "price" vector $\mathbf{W}_1$ represents a schedule of payments for each adopting OEM, that is, how much to pay in the first period, how much in the second period, whether the fees are volume based, etc.

In Period 1, along with setting the price $\mathbf{W}_1$, the provider also decides to develop a new technology αT $(\alpha \geq 1)$ to be introduced in Period 2. Technology development requires time and substantial investment. Hence, the provider needs to initiate development during the first period, thus sending a credible signal to the market regarding the technology development decision. In practice, such signals materialize through trade shows and press releases. The development cost for an α enhancement is given by $C(\alpha)$; $C(\alpha)$ is increasing in α, and $C(1) = 0$.

Initially (at the beginning of Period 1), all the OEMs employ identical technology (i.e., standard process or know-how, with performance normalized to 1). This assumption enables us to isolate the impact of downstream competition on the technology introduction decisions without having to contend with the confounding effects of initial asymmetry. Still, our model allows possible asymmetries in technology usage in the subsequent period.

During each period, the OEMs compete for a common end-product market based on their end-product quality.[2] Our motivating examples drive this assumption on the importance of end-product performance (quality). Let Q_i^k be the quality of the end product manufactured by the ith OEM in period k $(k = 1, 2)$, and suppose that Q_i^k depends on both the technology[3] T_i^k employed by OEM i in period k, and the OEM's capabilities κ_i. That is, $Q_i^k = F(\kappa_i, T_i^k)$, $F(\kappa, T)$ increasing in κ and T.

The customers to whom the OEMs sell their end product are assumed to be quality conscious and favor the OEM that provides greater end-product quality. Hence, that OEM revenues and market share depend on both the OEM's end-product quality and the qualities of its competitors' end products. The market share of an OEM is determined through a *market share attraction model*:

$$\text{market share of } i\text{th OEM in period } k = \frac{Q_i^k}{\sum_{j=1}^n Q_j^k},$$

and his revenues through the part of the end-product market he has captured:

$$\begin{aligned}\text{revenue} = {} & (\text{total end-product market size in dollars})\\ & \times (\text{market share}).\end{aligned}$$

Market share attraction models (MSAs) are widely used in the marketing literature (Bell et al. 1975, Monahan 1987, Gruca and Sudharshan 1991) and have been shown to have excellent predictive power (Naert and Weverbergh 1981).

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[1] T represents the performance of a new process know-how, heavy equipment, architecture, or a combined system that realizes an improvement in the manufactured end product.

[2] Although we assume a competition mechanism based on quality, as we show in Erat and Kavadias (2004), subject to mild regularity conditions, the fundamental insight of our model remains intact for different forms of competition. Two widely used competition mechanisms that conform to these regularity conditions are the case where technology reduces manufacturing costs and the OEMs engage in differentiated Bertrand (price) competition, and the case where they engage in Cournot (quantity) competition.

[3] Note that T_i^k depends on the adoption decision of OEM i in the following way:

$$T_i^1 = \begin{cases} T & \text{if OEM } i \text{ adopted in Period 1,} \\ 1 & \text{otherwise,} \end{cases} \quad \text{and}$$

$$T_i^2 = \begin{cases} \alpha T & \text{if OEM } i \text{ adopted in Period 2,} \\ T_i^1 & \text{otherwise.} \end{cases}$$

Given this structure of competition, in each period, all the n OEMs simultaneously[4] decide on technology adoption based on their increases in revenues due to adoption. Note that in the first period, each OEM makes the decision accounting for the current (Period 1) and future (Period 2) payoffs, and in the second period, the decision rests on the past choices and potential revenues from additional adoption. Example 1 given in the online appendix on the *Management Science* website at http://mansci.pubs.informs.org/ecompanion.html illustrates this mechanism of technology adoption with a basic single-period example.

The size of the common end-product market (measured in dollars) for which the OEMs compete in the first period is normalized to 1 and in the second period is m. Furthermore, while in many industries the size of the end-product market may be relatively unaffected by the underlying technology,[5] it may be the case for some that end-product market size increases due to the enhancement of the underlying technology. Hence, we assume that the end-product market size in the second period is $m = m(\alpha)$, where $m(\cdot)$ is a nondecreasing function.

We assume that the OEMs have an identical discount factor for their future profits. Suppose that the technology provider announces that the next version (αT) is to be introduced at t_a. Because of uncertainty in technology development, however, there is some probability p that the launch date slips by d. Furthermore, the extent of technology development that the provider undertakes may affect the probability of launch delay; that is, $p = p(\alpha)$, where $p(\cdot)$ is a nonincreasing function. OEMs discount second-period payoffs by $\delta(t)$ if the actual time of introduction of future technology is t. The possibility of a delayed launch, however, renders the discount factor uncertain as well. Let $\delta = E[\delta(t)] = (1-p)\delta(t_a) + p\delta(t_a + d)$. Hence, δ is a decreasing linear function of p.

Figure 1 **Timing of the Game**

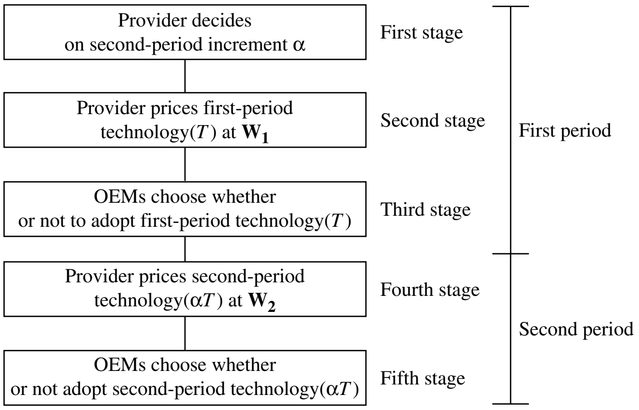

Figure 1 summarizes the timing of the game. In the first period of the game, the provider launches technology T and decides on the next technology, αT. The provider prices technology T at $\mathbf{W}_1$, and the OEMs decide on technology adoption.

In the second period, the provider introduces the newly developed technology αT and prices it at $\mathbf{W}_2$. OEMs again decide on adoption of the new technology αT. All the preceding decisions are assumed to be common knowledge.

4. Base-Case Model

The general model as presented above encompasses multiple licensing mechanisms (for instance, the price vector $\mathbf{W}_1$ and $\mathbf{W}_2$ may model licensing mechanisms such as volume-based royalty, one-time fee, per period license fee, possible upgrade prices, etc.) and varied OEM market structures (suitable choices of κ and $F(\cdot)$ may be utilized to model the extent and nature of OEM capabilities and different types of asymmetric OEM market structures). To gradually build our intuition while maintaining analytical tractability, we start our analysis by considering a relatively simpler base-case model. Subsequently, §5 relaxes the base-case assumptions one at a time to obtain additional insights as well as to verify the robustness of our results.

The base-case assumptions given in Table 1 are grouped into two major categories: those relating to the nature of the technology and its impact on the end-product market and those relating to the OEM market structure.

By Assumption T.1, the end-product market size m and the delay probability p are exogenously specified constants unaffected by the future technological enhancement α. Assumption T.2 implies that the provider does not offer any special upgrade

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[4] In game-theoretic terms, the simultaneous decision assumption is equivalent to assuming lack of communication among the industrial customers. Although the lack of communication between industrial customers might be valid in most settings, the applicability of our results extends to even more general situations. We show in Erat and Kavadias (2004) that the assumption of simultaneous decision making with regard to the OEMs is not critical for our results and that all our results hold even if we assume that the industrial customers sequentially decide on technology adoption in some arbitrary, prespecified order. For this corresponding sequential version of the game, the OEMs' payoff structure is the same as in the simultaneous game.

[5] In our main motivating example of carpet manufacturers who use DuPont's Sorona GT, it is unlikely that the total market for carpets is impacted by the process innovation (external events, e.g., how well the real estate business is doing, are possibly going to have a greater impact on market size for carpets). Additionally, in the high-tech industry of cell phone manufacturers it seems less likely that the total number of cell phone buyers will increase because of ARM's protocol innovation.

Table 1 **Base-Case Assumptions**

Nature of technology	OEM market structure
T.1. The technology does not have a significant impact on the end-product market size or the delay probability.	S.1. The capabilities of all the OEMs are identical.
T.2. The technology provider does not offer any special upgrade price.	
T.3. The technology provider uses a fixed one-time payment scheme.	

prices. Furthermore, by Assumption T.3, the technology provider transfers lifetime usage rights of the technology to the adopting OEM for a one-time payment. Thus, the price vectors $\mathbf{W}_1$ and $\mathbf{W}_2$ have only one component, W_1 and W_2, respectively, representing the one-time payment. Finally, by Assumption S.1, $\kappa_i = \kappa$ for all i. Thus, the quality $Q_i^k = F(\kappa, T_i^k) = F_\kappa(T_i^k)$. We normalize the technology T by defining a normalized technology $T' = F_\kappa(T)$. Hence, without loss of generality, in the base-case, we let the quality of the end product be $Q = T$.

Sections 4.1 and 4.2 derive the optimal pricing decisions and the technology development decision, respectively, in two steps: (a) Theorem 1 gives the optimal pricing decision, given the technology development decision in stage 1, and (b) a mathematical program is formulated to solve for the optimal technology development and pricing scheme that maximizes the monopolist's overall profits. We focus on the subgame perfect Nash equilibria in pure strategies for this multistage game.

4.1. Technology Pricing

In this section, we derive and analyze the optimal pricing in both periods and the associated adoption equilibria for an arbitrary technology development decision. We provide the main notations in Table 2 (for an extended list of notations, see the appendix).

Theorem 1. *Given an arbitrary first-period technology T and second-period technology αT:*

(1) *If $\pi_a(\alpha) \le \pi_p(\alpha)$, then there exists an $f^*(\alpha)$ (<1) such that the technology provider prices the technologies to induce $nf^*(\alpha)$ OEMs to adopt technology T in the first period and the remaining $n(1 - f^*(\alpha))$ OEMs to adopt technology αT in the second period. Furthermore, there are $\binom{n}{nf^*}$ Nash equilibria.*[6]

(2) *If $\pi_a(\alpha) > \pi_p(\alpha)$, then the technology provider optimally sells the technologies T and αT to all the OEMs in both periods.*

Theorem 1 derives the optimal pricing policy, given the technology road map. The technology provider may have announced a technology road map some generations ahead for strategic reasons other than short-term profit maximization.[7] Still, technology providers retain considerable flexibility in pricing/licensing. For example, in the microprocessor industry, ARM has set out a road map for future generations of its technology TrustZone (launched in the second quarter of 2005). However, the pricing schedule (including the licensing fees) for the technology was not announced until the beginning of 2005 (see the ARM website at http://www.arm.com/miscPDFs/4136.pdf).

Theorem 1 demonstrates that the technology provider may either (a) induce all the OEMs to adopt in both periods or (b) induce adoption by only a fraction of the OEMs in the first period, and induce the remaining OEMs to skip the first-period technology and move directly to the second-period technology. We call the former scenario the *saturation strategy* and the latter the *leapfrogging strategy*.

The leapfrogging strategy is a general form of intertemporal price discrimination, a mechanism that the technology provider employs for revenue maximization. The possibility of price discrimination in our model is intuitive despite the assumption of an industrial market where all OEMs employ the same initial technology. The incremental benefit of an OEM (from adopting the technology) is decreasing in the number of adopters. Thus, the provider is able to induce a prisoner's dillema structure in the adoption game (because in a prisoner's dillema, the "confess" strategy has higher payoffs if the player is the only one playing it).[8]

In the leapfrogging strategy, to induce fewer OEMs to adopt initially, the provider sets a high enough price for the first-period technology, thus dividing the OEMs into two groups in the post-introduction era: (i) the technologically advanced (i.e., OEMs who

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[6] The multiplicity of the equilibria ($\binom{n}{nf^*}$ equilibria) is a direct result of our assumption of symmetric OEMs and simultaneous decision making. Although the nonuniqueness of equilibria may curtail the predictive power of general game-theoretic models (for instance, the classic Hawk-Dove game has two equilibria), our study does not suffer very much from this shortcoming, as our focus is on the provider's introduction decisions. For this purpose, the issue of which equilibrium would emerge, although theoretically interesting, is less relevant because irrespective of the equilibrium chosen, the technology supplier gains the same revenues and will use the same pricing and introduction strategy. The game where OEMs sequentially make decisions has a unique equilibrium that is qualitatively identical to the equilibria given in Theorem 1 (Erat and Kavadias 2004).

[7] For instance, severe pressure to constantly innovate rapidly so as to maintain a monopoly position.

[8] Examples 1 and 2 given in the appendix illustrate that the incremental benefit for an OEM (from adoption) decreases the number of adopters and highlights the consequent prisoner's dillema structure of the adoption game.

Table 2 Base-Case Model: List of Notations

f	Fraction of adopters in the first period
$W_1^p(f,\alpha)=\left(\frac{T}{\theta_f}-\frac{1}{\theta_f-T+1}\right)+\delta m\frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ $W_2^p(f,\alpha)=m\left(\frac{\alpha}{\gamma_f}-\frac{1}{\gamma_f T-\alpha T+1}\right)$	Prices when $f<1$ (i.e., partial adoption)
$W_1^a=\frac{1}{n}-\frac{1}{nT-T+1}$ $W_2^a(\alpha)=m\left(\frac{1}{n}-\frac{1}{n\alpha-\alpha+1}\right)$	Prices when $f=1$ (i.e., complete adoption)
F	Feasible set for f
$\pi_p(\alpha)=\max_{f\in F}\{n[fW_1^p(f,\alpha)+(1-f)W_2^p(f,\alpha)]\}$	Maximal revenue when $f<1$
$f^*(\alpha)=\arg\max_{f\in F}\{fW_1^p(f,\alpha)+(1-f)W_2^p(f,\alpha)\}$	Optimal fraction of first-period adopters when $f<1$
$\pi_a(\alpha)=n(W_1^a+W_2^a(\alpha))$	Maximal revenue when $f=1$

adopted in Period 1 and consequently own a technology that is superior to the current average technology in the market) and (ii) the technological laggards (i.e., OEMs who because of nonadoption in Period 1 own a technology that is inferior compared to the current average technology). In the second period, the laggards' marginal benefit from adoption is higher (compared to the technologically advanced) because they currently have the inferior technology. Hence, the provider again can set a high price and this time induce only the laggards to adopt. Our result adds to the industrial organization theory of price discrimination by extending it to the case of competing customers.

Proposition 1 reveals how the choice of the revenue maximization strategy depends on the performance improvement that the second-period technology provides.

Proposition 1. *The leapfrogging strategy is optimal if and only if the technology improvement introduced in the second period is lower than a threshold* α_t.

Intuitively, if the future technology does not significantly enhance the end-product performance, then the provider would "milk" the maximum revenue from the current (initial) technology. However, if the future technology enhancement is large, even the first-period adopters would have sufficient incentive to adopt the future offering when it is introduced in the second period. Hence, the provider induces saturation in the first period.

For the special case $\alpha=1$, Corollary 1 characterizes the multiperiod introduction of a new technology.

Corollary 1. *When a single technology is introduced over two periods, the technology provider follows the leapfrogging strategy. Furthermore, the optimal price path is decreasing over time.*

Corollary 1 examines an interesting special case: the diffusion of a single new technology into a competitive market under the assumption that prices are constant within a period. Reinganum (1981a) arrived at a similar notion of diffusion equilibria by assuming that the price path is decreasing over time. Our result demonstrates that a decreasing price path is indeed optimal for the provider and thus offers an additional explanation for the empirically observed diffusion and declining price paths in industrial goods.

Proposition 2 characterizes the sensitivity of the optimal technology pricing with respect to the technology performance improvement α.

Proposition 2. (i) *The optimal first-period price is higher if the corresponding performance improvement is below the threshold* α_t. $W_1^*(\alpha_1)>W_1^*(\alpha_2)$ *if* $\alpha_1<\alpha_t<\alpha_2$.

(ii) *The second-period price* $W_2^*(\alpha)$ *is discontinuous and decreasing at the threshold* α_t *(i.e.,* $W_2^*(\alpha_t-)>W_2^*(\alpha_t+)$*).*[9]

Intuitively, a higher-performing future technology reduces the first-period prices because only through reducing the current price can the provider induce the customers not to wait for the future technology. Hence, OEMs pay less for the current technology when the future offerings are significantly better than the current technology.

Setting lower prices for a superior (future) technology, however, appears to be nonintuitive. This result stems from the provider inducing an "adopt-now" reaction. Under the saturation strategy, all customers adopt initially and would thus benefit less from improving their technology again in the second period. Subsequently, the provider optimally reduces the second-period price.

Propositions 3–5 build our intuition regarding the effects of development uncertainty and end-product market size on the introduction strategy. Assume a

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[9] $Q(\alpha-)$ and $Q(\alpha+)$ are the left- and right-hand limits of $Q(x)$ at α.

Table 3 Sensitivity Results

		δ or $-$(delay probability)	Future market size (m)
Claim 1	α_t	↗	↗
Claim 2	f^*	↗	↘
Claim 3	W_1	↗	↗
Claim 4	W_2	↗	↗
Claim 5	π_{provider}	↗	↗
Claim 6	π_{OEM}	↘	—

customer discount factor δ, probability of delayed launch p, future end-product market size m, technology enhancement α, and the associated technology progress threshold $\alpha_t(\delta, m)$. Recall that in our model the (expected) discount factor δ is decreasing in the probability of delayed launch.

Proposition 3. *The probability of delayed launch and the future end-product market size affect the technology progress threshold, initial adopters, first- and second-period prices, and provider and OEM revenues, according to Table* 3.

We focus on the leapfrogging strategy region (i.e., $\alpha < \alpha_t(\delta, m)$) because for the saturation region (i.e., $\alpha > \alpha_t(\delta, m)$), any small perturbation still results in full adoption. Claim 1 analyzes the effect of lower probability of delayed launch and/or larger size of the end-product market: The leapfrogging strategy becomes optimal for a wider range of second-period technologies. Higher probability of delayed launch decreases an OEM's valuation of future revenues. Hence, more perceived value in the future, due to either higher m or lower probability of delayed launch, enables the provider to induce leapfrogging.

The intertemporal price discrimination literature argues that monopolists may lose market power when facing rational customers with a high enough discount factor (Coase 1972, Bagnoli et al. 1989, Guth and Ritzberger 1998). Coase (1972) conjectured that this could even lead to competitive and thus efficient market results. A number of situations (for example, finite collection of customers, finite capacity supplier, and increasing marginal cost of production) have been identified where this conjecture fails. Our findings add to this list by demonstrating that downstream competition enables the monopolist provider to undertake a credible intertemporal price discrimination strategy even when customers have a high discount factor.

Claim 2 shows that a lower probability of delayed launch results in more customers adopting initially, and an increase in end-product market size leads to fewer customers adopting early. An OEM that enters the second period as technologically inferior (i.e., a first-period nonadopter) is exploited by the provider and accrues lower second-period profits as compared to the second-period profits of an OEM who adopted in the first period. Hence, when the probability of delayed launch decreases, the present value of the second-period profits increases, resulting in OEMs favoring early adoption to avoid being exploited by the provider in the second period. But if m increases, the customers would prefer to own the state-of-the-art technology in the period with the larger end-product market and would adopt late.

Claims 3 and 4 characterize the effects on the prices. The intuition is similar to the one presented in Claim 2. When the probability of delayed launch decreases (i.e., δ increases), customers increase their valuation of the second-period profits (and of the second-period price). Hence, the OEMs will pay a premium for early adoption (and for avoiding the second-period price). Also, from Claim 2, we know that with a decrease in the probability of delayed launch, the number of early adopters increases or, equivalently, the number of late adopters decreases. But given that the adoption price decreases with the number of adopters, the lower number of adopters in the second period allows the provider to charge higher second-period prices.

Similarly, when m increases, OEMs would pay more for the second-period technology because there is a larger end-product market to sell to. Also, from Claim 2, increasing m leads to fewer early adopters. This lower number of first-period adopters enables the provider to charge a higher price for the first-period technology.

Claim 5 shows the change in provider revenues. A decrease in the probability of delayed launch leads to an increase in an OEM's valuation of future profits. The provider anticipates that the OEMs have a greater incentive for avoiding technological inferiority and paying high prices for future technology. Hence, the provider can charge a price premium for the first-period technology. This price premium increases both the revenue per customer and the total revenue. Similarly, a larger future end-product market size increases the customer incentives to adopt in the second period. The provider anticipates this customer reaction and charges a premium, gaining higher revenues.

Claim 6 trivially follows from Claim 5 because in the base-case, the sum of revenues of the provider and the customers is constant ($=1+m$).

Proposition 4. *The provider's revenue is convex decreasing in the probability of launch delays.*

Intuitively, a higher probability of delays in technology introduction renders the customers less likely to be exploited[10] because the announcement of launching a better technology within a short time may not be credible (i.e., in game-theoretic terms, with higher probability of delays, the threat strategy of launching a better technology within a short time is not credible). Our findings relate to an important managerial implication: Not only do the revenues decrease with an increase in the probability of delays in the launch schedule, but the marginal decrease is decreasing as well. In essence, downstream competition magnifies the effect that reliability in time to market has on profitability, penalizes the provider even for relatively small delay probabilities, and confirms Hendricks and Singhal's (1997) observation about the substantial negative impact of delays in product launches.

Proposition 5. *The provider revenue is not increasing for every technology improvement* (α). *That is,* $\{\alpha_1 \geq \alpha_2\} \nRightarrow \{\pi_p(\alpha_1) \geq \pi_p(\alpha_2)\}$.

The impact on the provider revenues of offering a superior second-period technology can be mixed. When the second-period technology is a minor improvement (low α), OEMs face large competitive pressure to adopt early and avoid becoming technological laggards, but for higher α values, this competitive pressure for early adoption declines and the provider cannot extract the high premium for early adoption. Dhebar (1996) offers qualitative insights into a similar phenomenon in a durable goods market with heterogeneous customers. He argues that too-fast introduction of new, improved versions can lead to customer regret and in the long term harm the technology provider. He suggests that there is an "optimal" pace of product improvement and recommends that decisions on product improvement be accompanied by a consideration of demand side effects. Our result demonstrates that in B2B technology markets with competing customers, setting a suboptimal pace of product improvement can reduce the technology provider's profits by skewing the incentives among the customers.[11]

4.2. Technology Development

In this section, we continue our examination of the base-case model and examine the provider's decision regarding the development effort. In certain industries, technology road maps are traditionally not announced, allowing the technology providers to retain considerable flexibility in deciding both technology development and technology pricing in each period (e.g., our DuPont example from the chemicals industry).

Assume a deterministic cost of development $C(\alpha)$. With uncertain development costs, the results presented below remain valid, with $C(\alpha)$ redefined as the expected cost of an α increment.[12]

The technology provider's technology development decision can be formulated as follows:[13]

$$\alpha^* = \arg\max_{\alpha \geq 1}\{\max(\pi_p(\alpha), \pi_a(\alpha)) - c(\alpha)\}. \quad (1)$$

We prove the next two propositions for quadratic development costs $C(\alpha) = c(\alpha - 1)^2$. The assumption of quadratic costs is intended only for illustration.[14]

Proposition 6. *The optimal development effort* $\alpha^*(c)$ *is decreasing in* c.

Intuitively, the provider improves the technology in smaller increments when the development cost is high. In the limit, as the development costs become very large, the provider does not pursue significant advances and sells only minor improvements in future periods.

Proposition 7. *The technology provider employs a leapfrogging strategy if and only if* c *is greater than a threshold* c_t.

Substantial development costs force the provider to choose a development effort α^* that is relatively small (Proposition 6). If α^* is below the threshold α_t, then Proposition 1 suggests a leapfrogging strategy. Thus, in mature markets where the development costs are substantial, it is optimal to slowly diffuse the current technology through a leapfrogging strategy.

Proposition 8 offers a sensitivity analysis of the development effort with respect to the probability of delayed introduction and the end-product market size.

Proposition 8. *The optimal development effort* $\alpha^* \cdot (\delta(p), m)$ *is an increasing function of the probability of delayed introduction and an increasing function of* m.

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[10] Consider the limiting case $p = 1$ and $d = \infty$ (i.e., the technology improvement is never introduced). Then the actual announced date of introduction has no effect on the customers' decision.

[11] The authors are grateful to one of our referees, who pointed out the similarity between Proposition 5 and Dhebar (1996).

[12] For instance, suppose that $G(\alpha, x)$ is the probability that the cost of developing αT is less than or equal to x (i.e., $G(\alpha, x)$ is the c.d.f.). Then, define $C(\alpha) = E[\text{costs for } \alpha \text{ increment}] = \int_0^\infty x\, dG(\alpha, x)$.

[13] Note that we assume that the technology development decision is made before the first pricing decision. However, the order in which the provider makes the development decision and the first-period pricing decision are irrelevant because for an arbitrary function $\phi(.,.)$, $\max_{\alpha, W_1} \phi(\alpha, W_1) = \max_\alpha \max_{W_1} \phi(\alpha, W_1) = \max_{W_1} \max_\alpha \phi(\alpha, W_1)$ if the maximum is attained.

[14] Any other parameterization of costs of the form $C(\theta, \alpha)$ would be sufficient to prove Propositions 6 and 7, assuming the costs to be supermodular in (θ, α).

For instance, consider the family of nondecreasing cost functions $\lambda G(\alpha)$ indexed by the parameter λ. In this case, equivalent statements of Propositions 6 and 7 would be (a) the optimal development effort $\alpha^*(\lambda)$ is a decreasing function of λ, and (b) the technology provider employs a leapfrogging strategy if λ is above a threshold λ_t.

A lower probability of delayed introduction drives early adoption and allows the provider to charge premiums for early adoption, as shown in Claim 4 of Proposition 3. This allows the technology provider to gain higher revenues without necessarily committing more resources to development. Thus, with a lower probability of delayed introduction, the provider saves on the extra development costs while gaining additional revenue due to the early adoption premium.

In contrast, with an increase in future end-product market size, customers would be averse to being technologically inferior in the second period, allowing the provider to charge a higher price. Therefore, providing a superior second-period technology when the OEMs wish to have the state-of-art technology (i.e., when market size is larger) generates additional revenues.

5. Extensions and Generalizability

In §4, we showed the existence of two distinct strategies—leapfrogging and saturation—that a technology provider undertakes when introducing a new technology to a market of competing OEMs. The choice of the optimal strategy was shown to depend on the magnitude of future technological progress or, equivalently, on the costs, with incremental technological progress or large technology development costs dictating a leapfrogging strategy and the converse dictating a saturation strategy.

In this section, we extend our base case to study the generalizability of our conclusions and expand the scope of our findings. The extensions that follow do not explicitly consider the development costs, and it is assumed that the technology road map is fixed. However, as in §4.2, if the development costs are assumed to be quadratic (i.e., $C(\alpha) = c(\alpha-1)^2$), then the optimal technology development decision $\alpha^*(c)$ is decreasing[15] in c. Thus, any statement about technology enhancement α has an equivalent result in terms of the cost of development c.

We group the extensions with respect to two features of technology markets—the nature of the technology and the structural characteristics of the OEM market—corresponding to the two sets of Assumptions T.1–T.3 and S.1 we made in the base case.

5.1. Nature of Technology

The base case assumes several things: (i) the size of the end-product market m and the delay probability p are independent of the technology αT (i.e., there is no demand growth because of the innovation, and undertaking larger development does not increase the probability of delays); (ii) there is no possibility of special upgrade prices; (iii) the technology is obtained for a one-time fixed lifetime usage fee; and (iv) OEMs can integrate the technology into their current manufacturing process without cost.

When the technology provider undertakes a greater development effort (i.e., α is large), it is likely that the probability of the delayed launch increases. Similarly, introducing a superior technology that enhances the OEMs' end-product quality by a greater amount leads to an enhancement in demand and market growth.

The ability to offer upgrades is often an inherent feature of the technology or the industry.[16] For instance, in the case of architectures or IP rights, upgrading may not be feasible because of issues such as backward compatibility. In industries such as software (e.g., SAP), however, the existing practice may restrict the technology provider to always offering upgrades. Also, in many business contexts, the existence of secondary markets might ensure an implicit upgrading mechanism.[17]

In technology markets where the physical component (in addition to any IP usage rights) is sold, typically one "unit of technology" is required to manufacture one unit of the end product. In such scenarios, the technology provider may set per period usage fees or volume-based royalties. In addition, an OEM still may have to incur substantial costs[18] to integrate a newly adopted technology into its current processes.

We consider these aspects in the three extensions that follow.

Demand Enhancement and Delay Probabilities (Assumption T.1). Assume that the second-period end-product market size is $m(\alpha)$ and that the probability of delayed introduction of technology enhancement α is $p(\alpha)$. The results of the "pricing game" given in §4.1 do not change because αT is assumed fixed in the analysis. Therefore, the main insight (i.e., leapfrogging versus saturation, depending on the technological progress) remains valid.

Assume quadratic development costs $C(\alpha) = c(\alpha-1)^2$. Then, with respect to the pricing and development game presented in §4.2, the optimal development decision α^* is $\arg\max_\alpha\{\pi(\alpha) - c(\alpha-1)^2\}$. However, because $-c(\alpha-1)^2$ is submodular in (c, α), $\alpha^*(c)$ is decreasing in c (Theorem 6 in Topkis 1978).

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[15] $\alpha^*(c) = \max_\alpha\{\pi(\alpha) - c(\alpha-1)^2\}$. Because $-c(\alpha-1)^2$ is submodular in (c, α), $\alpha^*(c)$ is decreasing in c (Theorem 6 in Topkis 1978).

[16] Kornish (2001) offers some attributes of a durable goods market that make upgrades infeasible.

[17] As an example, if the technology in question is heavy equipment, an OEM that acquired an early version may be able to sell it off in a secondary market before adopting the new version, thus upgrading at a lower price. For technologies based on IP rights, however, such secondary markets rarely exist, rendering an implicit upgrading unlikely.

[18] This cost might comprise integration costs, disruption costs incurred from switching to new technology, etc.

Hence, the dependence of m and p on α does not change the main insights (i.e., leapfrogging versus saturation, depending on the development cost c) of our model.

Upgrade Prices (Assumption T.2). Assume that in the second period the technology αT is priced at $W_2 - u$ if the adopting customer was utilizing technology T, and at W_2 if he was utilizing technology 1 (i.e., u is the price break for upgrading).[19] The following theorem analogous to Theorem 1 can be proved:

THEOREM 1′. *Given an arbitrary first-period technology T and second-period technology αT:*

(1) *If $\alpha \leq \alpha_t$, then the technology provider prices the technologies such that only some of the OEMs adopt technology T in the first period, while all the n OEMs adopt technology αT in the second period.*

(2) *If $\alpha > \alpha_t$, then the technology provider optimally induces all the n OEMs to adopt T in the first period and αT in the second period.*

When the future technology enhancement is below a threshold, the technology provider finds it optimal to induce only a fraction of the OEM market to adopt the current technology. Under this strategy, the second-period technology (αT) is sold to the first-period nonadopters and to the first-period adopters at a reduced upgrade price. Note that this optimal introduction strategy is structurally similar to the leapfrogging strategy because a part of the OEM market skips over one technology to adopt future offerings.

Kornish (2001) finds that a durable goods monopolist has a credible intertemporal price discrimination strategy only when the monopolist commits to never offer upgrades in the future. We find that downstream competition enables a credible intertemporal price discrimination strategy, even when such a commitment cannot be given and upgrades are feasible.

Per Period Usage Fees, Volume-Based Royalties, and Implementation Costs (Assumption T.3). An OEM that adopts a new technology (T or αT) incurs an integration cost c_I. The first-period technology T is priced at W_1, where W_1 is a per period usage fee (i.e., if an OEM uses technology T in both Periods 1 and 2, the OEM pays $2W_1$ to the technology provider).[20] The case of volume-based royalties is identical to the per period usage fees, and therefore shall not be discussed further. The general nature of this model makes it analytically intractable. Hence, we utilize numerical analysis to obtain additional insights.

Table 4 **Provider's Optimal Strategies with Per Period/Volume-Based Fee and Integration Costs**

	Enhancement α		
	Low	Medium	High
Provider's optimal strategy	No sale of αT	Leapfrog	Saturation

Table 4 summarizes the provider's optimal strategies contingent on the future technology enhancements. As can be observed, while the structure of our main result remains intact, an additional region (no sale of αT region) emerges when integration costs are allowed to be nonnegligible. In this region, which occurs for very marginal enhancements, the OEMs that adopted technology T do not have sufficient incentives to adopt αT because the marginal benefit from improving their technology is lower than the implementation cost incurred. As a strategic response, the provider induces all the OEMs to adopt the current (first-period) technology. Thus, the technology provider would not develop a new technology (αT, $\alpha > 1$) unless the improvement it can offer is above a threshold.

5.2. OEM Market Structure (Assumption S.1)

Next we consider OEMs that are heterogeneous with respect to their capabilities. This extension accounts for a richer set of industrial settings and reflects the structure of the market faced by technology providers such as ARM (in our motivating example). With heterogeneous capabilities, the quality of an OEM's end product Q depends on both the technology T employed by the OEM as well as its capabilities κ. That is, $Q = F(\kappa, T)$. Due to the complexity of this extension, we employ numerical analysis.

We distinguish between two types of capabilities: those that enhance the value of technology (such as product development capabilities) and those that act independently of the technology (such as supply chain efficiency). We call the former capabilities "technology-enhancing" (TE) capabilities and the latter "technology-independent" (TI) capabilities. TE capabilities moderate the effect of technology on performance quality, and we model them as multiplicative; that is, $Q = T \times \kappa$. TI capabilities act independently of the employed technology and have a more direct effect on quality, and hence, we represent them as additive; that is, $Q = T + \kappa$.

Corresponding to these two types of capabilities, we consider following OEM market structures: (i) *heterogeneity in TE capabilities*, that is, the OEMs are heterogeneous only in terms of their TE capabilities, and (ii) *heterogeneity in TI capabilities*, where the OEMs are heterogeneous only in terms of their TI capabilities.

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[19] That is, $\mathbf{W}_1 = \{W_1\}$ and $\mathbf{W}_2 = \{W_2, W_2 - u\}$.

[20] Note that we have assumed that the per period usage fee is fixed for a particular technology and independent of the period. This assumption, to our knowledge, is fairly realistic and conforms to the actual royalties found in practice. Furthermore, because our focus is on the strategic drivers of the introduction strategy, we do not micromodel all the possible parameters, including perhaps volume/time-based discounts, of royalty contracts.

Table 5 **Technology Introduction in Heterogeneous Markets**

Structure of OEM market	Low α					High α
Heterogeneity in TE capabilities						
H	Leapfrogging	Leapfrogging	Saturation	Saturation	Saturation	Saturation
L	Only T	Leapfrogging	Leapfrogging	Saturation	Only T	No sale
Heterogeneity in TI capabilities						
H	Only T	Leapfrogging	Leapfrogging	Saturation	Only T	No sale
L	Leapfrogging	Leapfrogging	Saturation	Saturation	Saturation	Saturation

For both these market structures, suppose that λn OEMs (high capability, or H OEMs) have capability $\kappa = \kappa_h$, and the remaining $(1-\lambda)n$ OEMs (low capability, or L OEMs) have capability $\kappa = \kappa_l$ ($\kappa_l < \kappa_h$). Normalize κ_l to 1 in the case of heterogeneity in TE capabilities and to 0 in the case of heterogeneity in TI capabilities.

Figures 2 and 3 in the appendix present examples from the many experiments conducted and illustrate the technology provider's optimal strategy as a function of future technology enhancements. The insights obtained from our experiments are summarized in Table 5.

Technology Enhancing Capability. With very small future technological increment, the L OEMs adopt only the initial technology because without TE capabilities they cannot leverage the future marginal technological improvements. The H OEMs, however, value the technology more and are induced to leapfrog even for small future technology increments. As future technology enhancement becomes larger, the technology provider might find it optimal to induce leapfrogging for both types of OEMs, thus milking the value of current technology over a longer duration. As the technology increment becomes still larger, H OEMs are induced to adopt both the technologies, whereas the L OEMs are induced to leapfrog. Intuitively, H OEMs value the technology more (because of their higher level of TE capabilities), enabling the provider to gain more revenues by selling to all of them. For very large values of future technology increments, the provider might find it optimal to effectively disregard the L OEMs and sell them only the initial technology, if any at all.

Technology-Independent Capability. With very small future technological increment, the H OEMs adopt only the initial technology because they have large TI capabilities anyway and do not need the marginal technology improvements to compete effectively. The L OEMs, however, lacking TI capabilities, value the technology more and are induced to leapfrog even for small future technology increments. As future technology enhancement becomes larger, the technology provider might find it optimal to induce leapfrogging for both types of OEMs, thus milking the value of current technology over a longer duration. As the technology increment becomes still larger, L OEMs are induced to adopt both the technologies, whereas the H OEMs are induced to leapfrog. Intuitively, L OEMs value the technology more (because of their lower level of TI capabilities), enabling the provider to gain more revenues by selling to all of them. For very large values of future technology increments, the provider might find it optimal to sell the H OEMs only the initial technology.

Comparing across the two types of market structures (heterogeneity in TI and in TE capabilities) in Table 5 also reveals an interesting insight. The equilibrium behavior of OEMs with high (low) TE capabilities is similar to the equilibrium behavior of OEMs with low (high) TI capabilities. The following observation identifies the main driver for this insight:

Observation 1. An OEM with high TE capabilities obtains higher marginal benefit from a given technology and hence has higher incentive to adopt compared to an OEM with low TE capabilities. An OEM with low TI capabilities obtains higher marginal benefit from a given technology and hence has higher incentive to adopt compared to an OEM with high TI capabilities.

This observation is a direct result of the fundamentally different nature of the capabilities. An OEM with higher TE capabilities has greater ability to exploit a technology, whereas an OEM with lower TI capability has greater need for technology to compete effectively. Observation 1, together with the optimal strategies outlined in Table 5, suggests two important managerial guidelines: (i) In technology markets with heterogeneous OEMs, technology providers should concentrate on OEMs that have high TE capabilities and/or OEMs that have low TI capabilities, and (ii) an OEM that has low TE capabilities can get left behind the competition in terms of technology.

6. Conclusions and Further Research

In this paper, we have examined the optimal technology introduction strategies for firms that introduce new process technologies or IP-based architecture/component technologies to industrial customers (OEMs). In such business contexts, OEMs compete in end-product performance, and the underlying technology has a significant impact on the end-product performance. Hence, the technology provider faces a demand endogenously formed by the adoption decisions and the strategic considerations of the OEMs. We formulated a two-period game-theoretic model to account for the two main features observed in industry: (i) downstream competition and (ii) introduction of technology (or technologies) over time.

In this setting, we derived the optimal technology introduction strategies. The main result suggests a twofold structure for the introduction strategies: Depending on the performance improvement that the future technology realizes, the technology provider either overprices initially and induces partial adoption (leapfrogging strategy), or prices low, thus providing sufficient incentives for all the industrial customers to adopt (saturating strategy). The structure is robust to relaxation of several of our assumptions.

On the theoretical level, we provide the first comprehensive framework, to our knowledge, that simultaneously accounts for the technology introduction and the associated technology adoption decisions. In addition, our results add to the classic industrial organization theory of intertemporal price discrimination by considering competitive downstream markets.

On the managerial side, starting from a base case and relaxing assumptions gradually, we build intuition around the phenomenon. Several key insights are drawn from our theoretical results. Still, as in any analytical model, translation from theory to practice must be done cautiously, factoring in the limitations that the modeling assumptions impose.

The structure of the optimal strategy suggests that the monopolist technology provider benefits from a "controlled diffusion" in the presence of either (a) significant technology development costs or (b) a technology road map precommitment that dictates future technology development through small incremental steps. The robustness of this key result to several extensions verifies its dominant nature. In the limit, when the same technology is offered over multiple periods, the technology provider finds it beneficial to limit the number of adopters in each period by utilizing a decreasing price path.

The probability of delayed introduction has a negative impact on the technology provider's profits. Our results regarding the convex decreasing structure of profits suggest a severe impact of even small probability of delays. Thus, the negative impact of delayed product launches is further exacerbated by downstream competition. This highlights the significance of gaining credibility and customer confidence through timely launches, a result that has been discussed in new product development (NPD) literature (Hendricks and Singhal 1997).

Providing better technologies, even if they come at no additional development cost, may not always be beneficial for the technology provider. Offering a superior technology in the future dilutes the internal competition in the downstream market by increasing the OEMs' strategic value of waiting (for the future technology). Hence, the provider should carefully choose the development effort that balances the OEMs' incentive to wait for better technologies with their incentive to preempt their competitors (Dhebar 1996).

Higher future market potential prompts the provider to undertake more development. Further, a smaller probability of delays in technology introduction enables the technology provider to gain higher profits with a lower development effort. Thus, by being reliable in product launch announcements, the technology provider increases its profits while simultaneously reducing the development effort.

We also have examined the robustness of our main insights by extending the model to incorporate more general aspects of technology markets. While our main results remain unchanged for these extensions, additional insights were developed, especially for the case of OEMs with heterogeneous capabilities. We identify that the technology provider benefits from inducing by OEMs with high TE capabilities (such as product development capabilities) or OEMs with low TI capabilities (such as supply chain efficiency or logistics capabilities).

Viewed from the perspective of adoption, OEMs adopt technologies if they can effectively leverage the technologies into their end products and/or they need the technologies to compensate for inadequate nontechnology-related capabilities. Thus, our model suggests that the presence of high TE capabilities and low TI capabilities is likely to be associated with advanced technologies. Further empirical work shall examine this hypothesized linkage between type of capabilities and process/component technology usage in industrial markets.

We have developed a parsimonious model to capture some of the key dimensions of the industrial technology introduction decision. Several open questions remain for future research. We have modeled two sources of development uncertainty—time and cost. Still, the technology provider and industrial customers know with certainty the performance of the second-period technology. While many firms do achieve this reduction in performance uncertainty by trading off with development time/cost uncertainty, analyzing the impact of performance uncertainty remains a fruitful avenue to pursue. In addition, while our extensions offer some preliminary results into the impact of different licensing mechanisms on adoption patterns, future research should address rationales for technology providers to use one licensing mechanism over another.

An online supplement to this paper is available on the *Management Science* website at http://mansci.pubs.informs.org/ecompanion.html.

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