

Joint Product Development and Inter-firm Innovation

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To Sajna, my wife
for standing by me through ups and downs
for being my most ardent believer and most patient listener
for loving me and for making my dreams hers
for everything.

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SUMMARY

This thesis examines the strategic drivers and processes governing the development of products and/or technologies by multiple economic entities. The thesis adopts an operational approach in addressing the question and examines the “how” of joint product development. For this purpose, the different mechanisms that enable joint product development - licensing, outsourced development, and codevelopment - are considered, and the focus is restricted to the analysis and characterization of the optimal management of joint product development mechanisms.

Regarding the mechanism of licensing, the thesis examines both its dynamic intertemporal implications (i.e., how licenses should be structured given that licensing will also occur in the future) as well as the role of the technology in question (i.e., how are licenses affected by the type of technology being licensed). Along the first dimension, the thesis finds that license fees (and the negotiation with potential licensees) may be structured so as to induce a “controlled diffusion” depending on the technology roadmap the provider firm has laid out for the future. On the second dimension, the study finds that when the technological solution being licensed requires minimal integration from the licensees side, it may be beneficial to restrict attention to a few potential licensees instead of licensing to the entire market.

On the codevelopment side, the thesis presents an original case study that uncovers some of the salient features present in many joint development efforts. Subsequently, a mathematical model is proposed that captures the key dimensions of the phenomenon that were identified through the case study. Analysis of the normative model reveals the key role of market and development uncertainty in structuring the formal contractual agreements and sharing the value created through the codevelopment effort.

CHAPTER I

INTRODUCTION

In several industries, product development requires collaboration with outside firms on a scale that was unimaginable until recently. The reasons for such large-scale collaboration and coordination are be numerous and may include demand-side drivers such as increased importance of fast product development and/or supply-side drivers such as greater degree of specialized capabilities; but trend towards collaboration seems unmistakable. The current study is motivated by this trend and examines the question “how should/do firms manage joint product development efforts?” Thus, the focus of this study lies in examining the operational aspect of effective management of joint product development efforts.

NSF, in a whitepaper entitled Science and Engineering Indicators (2004), states that non-equity-based, short-lived, alliances aimed towards product development is becoming increasingly common in industries such as biotechnology and information technology. Also, they find that while the inhouse funding for R&D has increased at a rate of 3.8% over the past 8 years, the funding for outsourced R&D has increased at a rate of 4.8% over the same period. Furthermore, firms such as Qualcomm (a leading provider of cellphone-related Intellectual Property), Texas Instruments (a leading provider of Digital Signal Processor solutions), and DuPont (a leading provider of chemical process licenses) earn a significant portion of their revenues from licensing core components and/or processes to outside vendors.

These trends seem to indicate that a significant fraction of product development efforts that used to occur within a single firm may be being replaced by product development processes that spans across firms. Three distinct industrial settings are given below to illustrate the broad scope of the phenomenon and to set the stage for the dissertation.

R1: In the market for desktop PC, a highly disintegrated industry, manufacturers (original equipment manufacturers) such as Dell routinely procure the core component, the microprocessor, from the component technology provider, Intel. Furthermore, Intel also licenses (sells) its components to multiple OEMs. This example illustrates a setting where the division of the product development responsibilities is unambiguous and where there is a “technology market,” with its associated market mechanisms such as pricing etc., to facilitate the transfer of technology between economic entities.

R2: IDEO, a firm which specializes in product/service design has recently emerged as a strong player in the customized-design business boasting a clientele which includes many Fortune 500 firms. In such a setting of outsourced development, the division of product development responsibilities is unambiguous. However, there is no “technology market,” and therefore, the price of each unique project is individually negotiated. Furthermore, the design developed for one client firm cannot usually be licensed to others.

R3: Recently, Delta Airlines collaborated with 3M to develop a flame-resistant paper that could potentially be licensed to airline carriers Kavadias and Erat (2005). This co-development project required the two firms to interact on a frequent basis so as to jointly develop a new product. The example illustrates an industrial setting where, before the project started, the division of product development effort was unknown. Furthermore, the expertise that each firm provided was unique and could not be acquired easily from any outside “technology market.”

These illustrative examples allow us to conceptualize the following broad types of industrial settings relevant to joint product development. The setting illustrated by **R1**, Dell-Intel, offers an example where the dependencies between development tasks is minimal (possibly due to well defined interfaces). Thus, it is possible to imagine a product development process composed of two relatively independent parts - Intel’s part consisting of developing the microprocessor, and Dell’s part consisting of integrating the components into a fully functional end-product. Furthermore, in this setting the capabilities required

for development are relatively widely available and not unique to a single firm (for instance a number of vendors other than Dell have similar or identical product development capabilities as Dell). Similarly, the setting illustrated by **R2** and **R3** fall into the top-right and bottom-right quadrant of the figure given below.

		Specificity of Capabilities	
		Low	High
Interconnectness of Development Tasks	Low	Dell-Intel	IDEO-Bank of America
	High	-	Delta-3M

Based on this typology of industrial contexts relevant to joint product development and the industrial examples given in **R1-3**, it can be observed that the mechanisms used to undertake joint product development may depend on the industrial context. For instance, with low interconnectness of development tasks and low specificity of capabilities, it becomes possible to have a hands-off collaboration that is facilitated through market-mediated mechanisms such as licensing. However, with low interconnectness of development tasks and high specificity of capabilities, even if a hands-off approach is adopted intense negotiations might be required to agree to licensing terms (since the capabilities and hence the product/technology that is being transferred is somewhat unique). This might lead to using an outsourced product development mechanism to operationalize joint product development in contexts of low interconnectness and high asset specificity. Lastly, with high interconnectness of development tasks and high specificity of capabilities it might not be possible, even with any amount of negotiation, to agree to contract terms before developing the product jointly. This might make the mechanism of codevelopment more suited for such contexts.

This dissertation takes an operational approach to understanding the strategic drivers and the processes governing the development of products and/or technologies by multiple economic entities. Thus, this dissertation attempts to answer the “how” of joint product development by focusing on how firms manage mechanisms such as licensing (illustrated in **R1**), outsourced product development (as in **R2**), and/or codevelopment (illustrated in **R3**) that enable joint product development. For this purpose, the rest of the thesis is

organized based on the type of mechanism and industry context it addresses.

The first two chapters of this thesis, §2 and §3, examine the setting illustrated by **R1**. In §2 the thesis examines the main drivers of a technology provider's (technology) development and introduction decision when she may license a stream of improving technologies to multiple competing OEMs. One of the main results found in such technology licensing context relates to the optimality of "controlled diffusion," i.e., inducing only a few OEMs to adopt a given technology in any period, if the future technology increments are not substantial. In addition, the study also finds that when future technology improvements are not expected to be large, the OEMs may demonstrate a technology leap-frogging behavior where they skip one technology only to adopt the next improvement.

The second chapter, §3, focuses exclusively on providers of component technologies, and examines the impact of operational variables related to the technology, such as the architecture and the level of technology improvement, on a technology provider's optimal licensing policy. The study illustrates that accounting for these operational variables may in general make a fixed-price plus volume-based royalties licensing scheme optimal. This important result conforms to empirical observations from past studies and stands in stark contrast to much of the theoretical results from licensing literature that predict the suboptimality of volume-based royalties.

The third chapter, §4, analyzes the setting illustrated by **R3** and formulates a normative model based on a case-study of the Delta-3M co-development project Kavadias and Erat (2005). The study explicitly accounts for NPD variables such as internal (development) and external (market) uncertainty and finds that it may be optimal to delay signing the revenue/cost sharing contract after the joint development effort has commenced depending on the level of internal and external uncertainty.

CHAPTER II

TECHNOLOGY INTRODUCTION AND CONTROLLED DIFFUSION: CASE OF INTER-TEMPORAL LICENSING

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.

The following motivating examples from two industries sets the stage for the study: In chemicals, DuPont recently has 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). 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 2/3/2003, Wall Street Journal 11/18/2003).

In electronics, a relatively medium-sized firm, namely ARM (Advanced RISC Machines), 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 chapter. 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 he manufactures (e.g., nylon, textiles, 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 customization features” (RCR Wireless News 3/10/2003). 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 who introduces new technologies to a market of OEMs with similar integration capabilities. We discuss two distinct scenarios: (a) technology providers who have committed to a technology road-map and decide on pricing in every introduction, and (b) technology providers who 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 non-adopters of currently offered technology to adopt future technological offerings. Since, a part of the OEM market (is induced to) pass over one technology to adopt the future technology, we term 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 who have superior (greater) capabilities, if these capabilities enhance the value of the employed technology (e.g., new product development capabilities) and (ii) on OEMs who have inferior (lower) capabilities, if these capabilities provide value independently of the technology (e.g., supply chain efficiency or logistics capabilities).

The findings in this chapter 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 the chapter is organized as follows: In §2.1 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 §2.2. The analysis of the base-case is presented in §2.3. §2.4 presents various extensions to base-case model. Finally, §2.5 concludes with the managerial implications, limitations of the model, and some future research directions.

2.1 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; third, the inter-temporal price discrimination literature, which has studied how firms selling to heterogeneous markets modify prices over time so as to extract maximum revenues.

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 the 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 (1981b,a) 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 where delaying the adoption decision can be accompanied by information collection so as to reduce the associated uncertainty. Since 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 result in greater profits and greater extent of technology adoption.

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 (sub-game perfect) equilibrium pricing strategy. In this chapter, 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 & development side, Krishnan and Ramachandran (2004) 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 customer regret and enable the monopolist to maintain a credible price-discrimination strategy.

Inter-temporal Price Discrimination:

Coase (1972) explores the inter-temporal 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 the three streams of literature discussed above focus either on new product introduction to non-strategic customers or on technology adoption decisions made by competing firms under exogenously determined adoption costs. In this chapter, 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.

2.2 *Model Setup*

Consider a monopolist technology provider who 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 inter-temporal 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 technology¹ 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, i.e., how much to pay in first period, how much in 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

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.

without having to contend with the confounding effects of initial asymmetry. Still, our model allows possible asymmetries in technology usage in the subsequent period.

Each period, the OEMs compete for a common end-product market based on their end-product quality². 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 i^{th} OEM in period k ($k = 1, 2$), and suppose Q_i^k depends on both (i) the technology³ T_i^k employed by OEM i in period k (ii) and his 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 who provides greater end-product quality. Hence, the OEM revenues and market share depend on both his end-product quality and the qualities of his competitors' end-products. The market share of an OEM is determined through a *Market Share Attraction Model*:

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

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

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

Market share attraction models (MSA) 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).

Given this structure of competition, in each period, all the n OEMs simultaneously⁴ decide on technology adoption based on their increase in revenues due to adoption. Note

²Although we assume a competition mechanism based on quality, as we show in Erat and Kavadias (2005), 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.

³Notice that T_i^k depends on the adoption decision of OEM i in the following way:
 $T_i^1 = \begin{cases} T & \text{if OEM } i \text{ adopted in period 1} \\ 1 & \text{otherwise.} \end{cases}$ and $T_i^2 = \begin{cases} \alpha T & \text{if OEM } i \text{ adopted in period 2} \\ T_i^1 & \text{otherwise.} \end{cases}$

⁴In 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 extend to even more general situations. We show in Erat and Kavadias (2005) 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

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 upon the past choices and potential revenues from additional adoption. Example 1 given in the Appendix A 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 technology⁵, 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 second period is $m = m(\alpha)$, where $m(\cdot)$ is a non-decreasing function.

We assume that the OEMs have an identical discount factor for their future profits. Suppose the technology provider announces that the next version (αT) is to be introduced at t_a . Due to 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, i.e., $p = p(\alpha)$ where $p(\cdot)$ is a non-increasing 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 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 . She 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

customers sequentially decide on technology adoption in some arbitrary pre-specified order. For this corresponding sequential version of the game, the OEMs' payoff structure is the same as in the simultaneous game.

⁵In 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, is possibly going to have a greater impact on market-size for carpets). Additionally in the hi-tech industry of cell phone manufacturers it seems less likely that the total number of cell phones buyers increase because of ARM's protocol innovation.

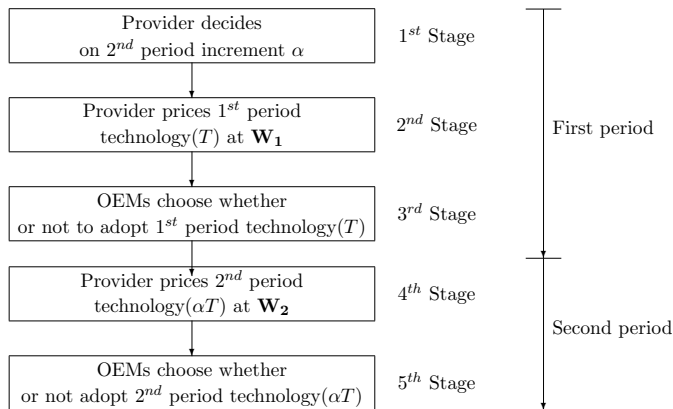


Figure 1: Timing of the game

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.

2.3 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, §2.4 relaxes the base-case assumptions one at a time in to obtain additional insights as well as to verify the robustness of our results.

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		

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 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 prices. Furthermore, by assumption **T.3**, the technology provider transfers life-time usage rights of the technology to the adopting OEM for a single 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 $Q = T$.

§2.3.1 and §2.3.2 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 multi-stage game.

2.3.1 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 refer to the Appendix A).

Table 2: Base-case: List of notations

f		: fraction of adopters in 1 st period
$W_1^p(f, \alpha)$	$= \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} \right) + \delta.m. \frac{(T-1)(\gamma_f-1)}{(T\gamma_f - T + 1)\gamma_f}$: 1 st period price to induce fraction $f (< 1)$ to adopt T
$W_2^p(f, \alpha)$	$= m. \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$: 2 nd period price to induce remaining $(1 - f)n$ OEMs to adopt αT
W_1^a	$= \frac{1}{n} - \frac{1}{nT - T + 1}$: 1 st period price that induces all the OEMs ($f = 1$) to adopt T
$W_2^a(\alpha)$	$= m. \left(\frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \right)$: 2 nd period price that induces all the OEMs ($f = 1$) to adopt αT
F		: Feasible set for f
$f^*(\alpha)$	$= \arg \max_{f \in F} \left\{ \begin{array}{l} fW_1^p(f, \alpha) \\ + (1 - f)W_2^p(f, \alpha) \end{array} \right\}$: Optimal fraction of 1 st period adopters when $f < 1$
$\pi_p(\alpha)$	$= n \left[\begin{array}{l} f^*(\alpha)W_1^p(f^*(\alpha), \alpha) \\ + (1 - f^*(\alpha))W_2^p(f^*(\alpha), \alpha) \end{array} \right]$: Maximal revenues when $f < 1$
$\pi_a(\alpha)$	$= n(W_1^a + W_2^a(\alpha))$: Maximal revenue when $f = 1$

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

- *if $\pi_a(\alpha) \leq \pi_p(\alpha)$, then there exists an $f^*(\alpha) (< 1)$ such that the technology provider prices the technologies so as to induce $n f^*(\alpha)$ OEMs to adopt technology T in first period and the remaining $n(1 - f^*(\alpha))$ OEMs adopt to technology αT in second period. Furthermore, there are $\binom{n}{n f^*}$ Nash equilibria⁶*
- *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 maximization⁷. 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 (which is scheduled for introduction in 2005). However, the pricing schedule (including the licensing fees) for the technology has not been announced yet (see ARM website:

⁶The multiplicity of the equilibria ($\binom{n}{n f^*}$ equilibria) is a direct result of our assumption of symmetric OEMs and simultaneous decision-making. Though the non-uniqueness of equilibria may curtail the predictive power of general game theoretic models (for instance the classic Hawk-Dove game has 2 equilibria), our study does not suffer very much from this shortcoming as our focus is on the provider's introduction decisions. And for this purpose, the issue of which equilibrium would emerge, though theoretically interesting, is less relevant, since 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, 2005).

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

www.arm.com/micsPDFS/4136.pdf).

Theorem 1 demonstrates that the technology provider may either (a) induce all the OEMs to adopt in both the periods, or (b) induce adoption by only a fraction of the OEMs in 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. Example 2 given in the Appendix A illustrates this two-fold structure.

The leapfrogging strategy is a general form of inter-temporal 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. 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 adopted in period 1 and consequently own a technology that is superior to the current average technology in the market) and the technological laggards (i.e., OEMs who due to non-adoption 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), since 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 second period is lower than a threshold α_t .*

Figure 2 illustrates the technology provider's total revenue based on the two possible strategies. The solid line corresponds to the saturation strategy and the dotted line to the leapfrogging strategy. Intuitively, if the future technology does not significantly enhance

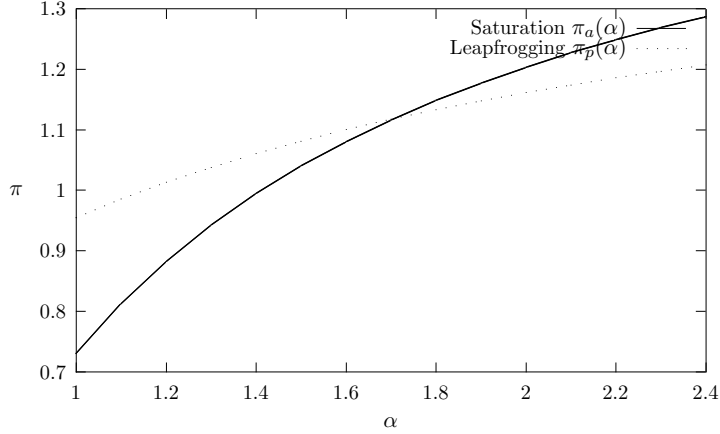


Figure 2: Provider revenues

the end-product performance, then the provider would “milk” the maximum revenue she can from the current (initial) technology.

The price charged for the current technology (T) depends on the technology development decision (α) only if the technology enhancement is incremental⁸ (i.e., $\alpha < \alpha_t$). This observation suggests an important managerial guideline: In industries with high technology progress (i.e., significant improvements between subsequent versions), the introduction decision shall be made so as to saturate the market and is independent of the future technology offerings, whereas in mature markets (i.e., markets where technology improves incrementally), the introduction decision shall create asymmetry in the OEM market depending on the future technology offerings.

For the special case $\alpha = 1$, Corollary 1 characterizes the multi-period 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.

⁸Observe from Table 2 that under the saturation regime, the initial price W_1^a is independent of the technology development decision (α). Further, the saturation strategy is optimal only if $\alpha > \alpha_t$.

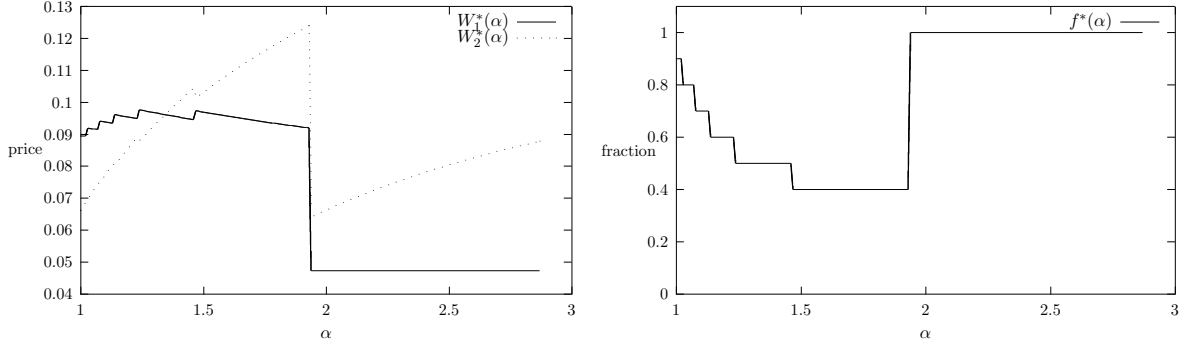


Figure 3: Optimal first- and second-period prices, and the fraction of adopters

Reinganum (1981b) 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, since 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 non-intuitive. 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.

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

Figure 3 illustrates how the first- and second-period prices (W_1^* and W_2^*), and the optimal splitting f^* are related to the performance increment α . The discontinuity (at $\alpha = 1.9$ in the figure) stems from the switching point of strategies at the threshold α_t .

Propositions 3-5 build our intuition regarding the effects of development uncertainty and end-product market size on the introduction strategy. Assume a 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 (i) technology progress threshold, (ii) initial adopters, (iii) first- and second-period prices, and (iv) provider and OEM revenues, according to the following table:*

		δ or $-$ (delay probability)	future market size (m)
CLAIM 1	α_t	\nearrow	\nearrow
CLAIM 2	f^*	\nearrow	\searrow
CLAIM 3	W_1	\nearrow	\nearrow
CLAIM 4	W_2	\nearrow	\nearrow
CLAIM 5	$\pi_{provider}$	\nearrow	\nearrow
CLAIM 6	π_{OEM}	\searrow	-

We focus on the leapfrogging strategy region (i.e., $\alpha < \alpha_t(\delta, m)$), since 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, either due to higher m or lower probability of delayed launch, enables the provider to induce leapfrogging.

The inter-temporal 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, increasing marginal cost of production) have been identified where this conjecture fails to hold. Our findings add to this list by demonstrating that downstream competition enables the monopolist provider to undertake a credible inter-temporal 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 who enters the second period as technologically inferior (i.e., a first-period non-adopter) 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 so as to avoid being exploited by the provider in the second period. On the other hand, 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, with 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 in 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 since 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 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 since in the base-case the sum of revenues of the provider and the customers is constant ($=1 + m$).

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

Intuitively, a higher probability of delays in technology introduction renders the customers less likely to be exploited¹⁰, since 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 does the revenues decrease with increase in the probability of delays in the launch schedule, the marginal decrease is decreasing as well. In essence, downstream competition magnifies the effect that reliability in time-to-market has on profitability and penalizes the provider even for relatively small delay probabilities. Hendricks and Singhal (1997) have found strong support for the substantial negative impact of delays in product launches (including industrial products).

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

¹⁰Consider 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.

The impact of offering a superior second-period technology on the provider revenues 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 technologically 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 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 sub-optimal pace of product improvement can reduce the technology provider’s profits by skewing the incentives among the customers.

2.3.2 Technology Development

In this section we continue the examination of the base-case 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 -increment¹¹.

The technology provider’s technology development decision can be formulated as follows:

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

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

¹¹For instance, suppose $G(\alpha, x)$ 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 $C(\alpha) = E[\text{costs for } \alpha \text{ increment}] = \int_0^\infty x dG(\alpha, x)$.

first-period pricing decision is irrelevant¹².

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. 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) ¹³.

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 leap-frogging 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 $\alpha^*(\delta(p), m)$ is an increasing function of the probability of delayed introduction and an increasing function of m .*

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

¹²Since for an arbitrary function $\phi(\cdot, \cdot)$, $\max_{\alpha, W_1} \phi(\alpha, W_1) = \max_{\alpha} \max_{W_1} \phi(\alpha, W_1) = \max_{W_1} \max_{\alpha} \phi(\alpha, W_1)$ if the maximum is attained.

¹³For instance, consider the family of non-decreasing 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 iff λ is above a threshold λ_t .

technology provider to gain higher revenues without necessarily committing more resources to development. Thus, with 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.

2.4 Extensions & Generalizability

In §2.3 we have shown 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. Our motivating examples have shaped the key structure and the assumptions of the base-case model. For instance, the Sorona GT example conforms very closely to the base-case assumptions.

In this section we extend the 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 §2.3.2, 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 decreasing¹⁴ 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

¹⁴ $\alpha^*(c) = \max_{\alpha} \{\pi(\alpha) - c(\alpha - 1)^2\}$. Since $-c(\alpha - 1)^2$ is submodular in (c, α) , $\alpha^*(c)$ is decreasing in c (Theorem 6 in Topkis, 1978).

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.

2.4.1 Nature of Technology (Assumption T.1, T.2, & T.3)

The base case assumes that (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 costlessly.

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

The ability to offer upgrades is often an inherent feature of the technology or the industry¹⁵. For instance, in the case of architectures or IP rights, upgrading may not be feasible due to issues such as backward compatibility. In industries such as software (e.g., SAP), however, the existing practice may restrict the technology provider to comply with always offering upgrades. Also, in many business contexts, the existence of secondary markets might ensure an implicit upgrading mechanism¹⁶.

In technology markets where the physical component (in addition to any intellectual property 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 costs¹⁷ to integrate a newly adopted technology into his current processes.

¹⁵Kornish (2001) offers some attributes of durable goods market that make upgrades infeasible.

¹⁶As an example, if the technology in question is heavy equipment, an OEM who 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.

¹⁷This cost might comprise integration costs, disruption costs incurred due to switching to new technology, etc.

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 §2.3.1 do not change since αT is assumed fixed in the analysis. Therefore, the main insight (i.e., leapfrogging vs. 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 §2.3.2, the optimal development decision α^* is $\arg \max_{\alpha} \{\pi(\alpha) - c(\alpha - 1)^2\}$. However, since $-c(\alpha - 1)^2$ is submodular in (c, α) , $\alpha^*(c)$ is decreasing in c (Theorem 6 in Topkis, 1978). Hence, the dependence of m and p on α does not change the main insights (i.e. leapfrogging vs. saturation depending on the development cost c) of our model¹⁸.

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. Then, the following theorem analogous to Theorem 1 can be proved:

Theorem 1' *Given an arbitrary first-period technology T and second-period technology αT*

- *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.*
- *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.*

Figure 4 illustrates the fraction of first-period adopters and the technology provider’s revenues as a function of second-period technology enhancement. If the future technology

¹⁸The argument also illustrates that in the entire chapter only two of the secondary results given in Proposition 8 may change if m is assumed to depend on α .

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

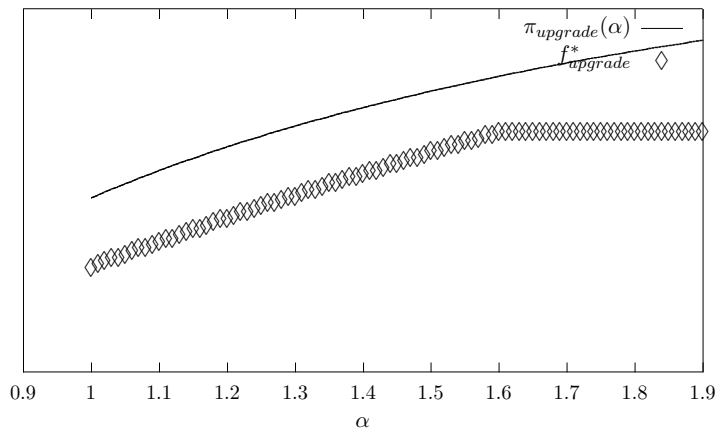


Figure 4: Revenues and optimal number of first period adopters

enhancement is below a threshold, it is 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 non-adopters *and* to the first-period adopters at a reduced upgrade price. Notice that this optimal introduction strategy is structurally similar to the leap-frogging strategy, since a part of the OEM market skips over one technology to adopt future offerings.

Kornish (2001) has found that a durable goods monopolist has a credible inter-temporal price discrimination strategy only when the monopolist commits to never offer upgrades in the future. We find that downstream competition enables a credible inter-temporal 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 who 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,

²⁰Note 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, since our focus is on the strategic drivers of the introduction strategy, we do not micro-model all the possible parameters, including perhaps volume/time-based discounts, of

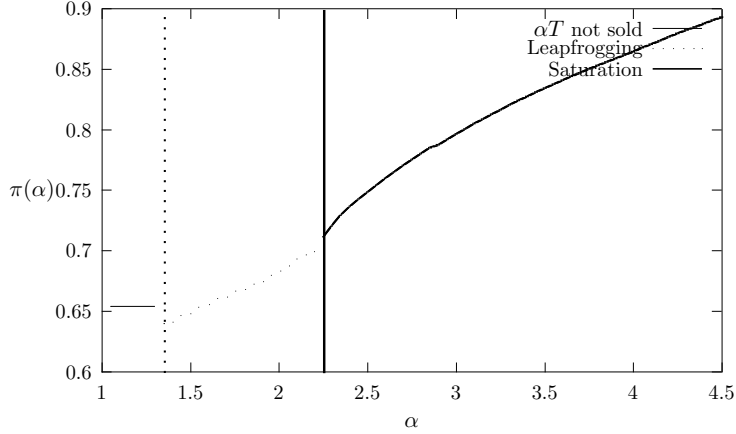


Figure 5: Revenues when price is per-period ($c_I = 0.04$, $T = 2$, $n = 6$, $\delta = m = 1$)

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.

Figure 5 presents an illustrative example. The structure of our main result remains intact. For very marginal enhancements, the OEMs who adopted technology T do not have sufficient incentives to adopt αT , since 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. The technology provider would not develop a new technology (αT , $\alpha > 1$) unless the improvement she can offer is above a threshold. For larger technology increments, leapfrogging becomes the optimal strategy to pursue. Finally, for very large technology increments, inducing full adoption in both the periods (i.e., saturation) becomes the attractive strategy.

The existence of per-period pricing or volume-based pricing and significant implementation costs impact the technology introduction strategy marginally and in an intuitive fashion. Still, only the basic insights are obtained from this extension, and additional research shall be undertaken in the future to examine the rationale for technology providers choosing one licensing mechanism over another (for instance, volume-based pricing instead of a lifetime usage fee).

royalty contracts.

2.4.2 OEM Market Structure (Assumption S.1)

Next, we consider OEMs who 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 his 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; i.e. $Q = T \times \kappa$. TI capabilities act independently of the employed technology and have a more direct effect on quality, and hence, we represent them as additive; i.e. $Q = T + \kappa$.

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.

For both these market structures, suppose 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 15 and 16 in the Appendix A present examples out of 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 3.

Table 3: Technology introduction in heterogeneous markets

Structure of OEM Market	Low α				High α		
	Heterogeneity in TE Capabilities	<i>H</i>	Leapfrogging	Leapfrogging	Saturation	Saturation	Saturation
<i>L</i>		Only T	Leapfrogging	Leapfrogging	Saturation	Only <i>T</i>	No sale
Heterogeneity in TI Capabilities	<i>H</i>	Only T	Leapfrogging	Leapfrogging	Saturation	Only <i>T</i>	No sale
	<i>L</i>	Leapfrogging	Leapfrogging	Saturation	Saturation	Saturation	Saturation

Technology Enhancing capability: With very low future technological increment, the *L* OEMs adopt only the initial technology, since without technology-enhancing capabilities they cannot leverage the future marginal technological improvements. The *H* OEMs, however, value the technology more and are induced to leapfrog for low future technology advancements. As future technology enhancement becomes higher, 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 technology increment becomes still higher, *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 technology-enhancing 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 at all.

Technology Independent capability: With very low future technological increment, the *H* OEMs adopt only the initial technology, since they have large technology-independent capabilities anyway and do not need the marginal technology improvements to compete effectively. The *L* OEMs, however, lacking technology-independent capabilities, value the technology more and are induced to leapfrog for low future technology advancements. As future technology enhancement becomes higher, 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 technology increment becomes still higher, *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 technology-independent 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 H OEMs and sell them only the initial technology.

Table 3 demonstrates that the structural insights from the base case holds. In addition, comparing across the two types of market structures (heterogeneity in TI capabilities and heterogeneity in TE capabilities) in Table 3 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 3, suggests two important managerial guidelines: (i) In technology markets with heterogeneous OEMs, technology providers should concentrate on OEMs who have high technology-enhancing capabilities and/or OEMs who have low technology-independent capabilities, and (ii) an OEM who has low technology-enhancing capabilities can get left behind his competition in terms of technology.

2.5 Conclusions: Implications for Technology Introduction

In this chapter 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 two-fold structure for the introduction strategies: depending on the performance improvement that the future technology realizes, the technology provider either over-prices 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 (IO) theory of inter-temporal 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 “slow diffusion” in the presence of either (a) significant technology development costs, or (b) a technology road-map pre-commitment 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 NPD literature (Hendricks and Singhal, 1997).

Providing better technologies, even if it comes 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 balance 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 lower development effort. Thus, by being reliable in their product launch announcements, the technology provider increases her 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 capabilities²¹. We identify that the technology provider benefits from inducing by OEMs with high technology-enhancing capabilities (such as product development capabilities) or OEMs with low technology-independent 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 non-technology related capabilities. Thus, our model suggests that the presence of high technology-enhancing capabilities and low technology-independent capabilities is likely to be associated with advanced technologies. Further empirical work

²¹We are grateful to Vish Krishnan and to the audience at the INFORMS 2004 deep-dive session for suggesting this extension.

shall examine this hypothesized linkage between type of capabilities and process/component technology usage in industrial markets.

CHAPTER III

TECHNOLOGY LICENSING AND LICENSE TYPES: CASE OF COMPONENT TECHNOLOGIES

Many industries exhibit a trend of disintegration over time, starting off vertically integrated, and gradually evolving towards a multi-tier disintegrated structure (Christensen, 1994; Christensen et al., 2002). End-product characteristics, such as their (modular) architecture, and market attributes, such as increased demand for variety, may drive this evolution of industry structure, during which many end-product manufacturers (original equipment manufacturers or OEMs) transform to effective integrators of components and processes that are procured from outside vendors (Schilling, 2000). The Desktop PC industry provides the canonical example of such a disintegration: OEMs like Dell focus on efficient integration/assembly, and procure even the core components from specialized technology firms such as Intel. In such settings, the technology providers who sell (or license) component technologies tend to dominate in their own markets, in contrast to their downstream counterparts (the OEMs) who compete, often intensely, for the end-product consumer.

In this article, we examine the strategic introduction and licensing decisions of technology providers who develop and sell (license) component technologies with an identifiable impact on the end-product performance. The following example from the electronics industry sets the stage for our study. Texas Instruments (TI) sells its Digital Signal Processor (DSP) solutions to multiple firms, such as Seagate, Maxtor, and Quantum. Industry reports reveal that 95% of all the programmable DSP chips sold into the high performance hard disk market are produced by TI (TI press release). However, TI's industrial customers compete intensely for the same end user market. Also, TI's component technologies have significantly altered the competitive dynamics in the hard disk industry: When Seagate started using TI's DSP in their product line, the trade press reported that "T320C2xLP DSP core-based uniprocessor replaces five chips normally inherent in Hard Disk Drives

(HDD). This uniprocessor design would allow Seagate to drive down costs and speed up the time to market for new drive designs in a high-volume market” (Electronic News 1996).

The example outlines the following business setting: a near-monopolist technology provider significantly alters the competitive dynamics in an end-product market by licensing a highly integrated core component to several competing firms (hereafter OEMs).

The degree of integration, however, need not be the only dimension that makes a component valuable to the OEMs. The DSP trade press commented on TI’s varied product offerings that “TMS320C64x(TM) DSP [offered by TI] operates at 1 GHz and is the ‘fastest DSP’ in the world,” (PR Newswire 03/15/2004) whereas TI’s TMS320C6412 “[has] a rich set of peripherals, including an on-chip Ethernet MAC” and “offers a combination of features that customers have found extremely attractive” (PR Newswire 11/17/2003).

These two typical product offerings allow us to build upon the seminal work of Ulrich (1995), and to conceptualize the strategic component development decisions along two dimensions: (i) *what does the component do*, or the level of integration offered by the component technology (for example, develop a DSP that does core-computing and multimedia specific tasks), and (ii) *how well does it do it*, or the performance quality offered by the underlying technology of a particular component (for example, develop a 1GHz DSP or equivalently use 45nm transistor technology in the component). Figure 6 illustrates these two fundamental dimensions of the development decisions in the context of DSPs targeted toward the scanner market.

The TI setting and its associated component positioning (i.e., integrated vs. performance) question is representative of numerous other industries and technologies as the following examples illustrate. In the microprocessor industry, Intel, citing their recent success with the “Centrino” processor (Centrino combined the traditional microprocessor with wireless function) has embarked on a strategy of “platformization” wherein the stated goal is to offer highly integrated complete solutions to their target markets (Economist, 5/12/2005).

In the hearing-instruments industry, there are around 7 to 8 major end-product manufacturers (OEMs), whereas the core component (transducer) is supplied primarily by a single technology provider, Knowles Electronics. According to Lotz (1998), the technology

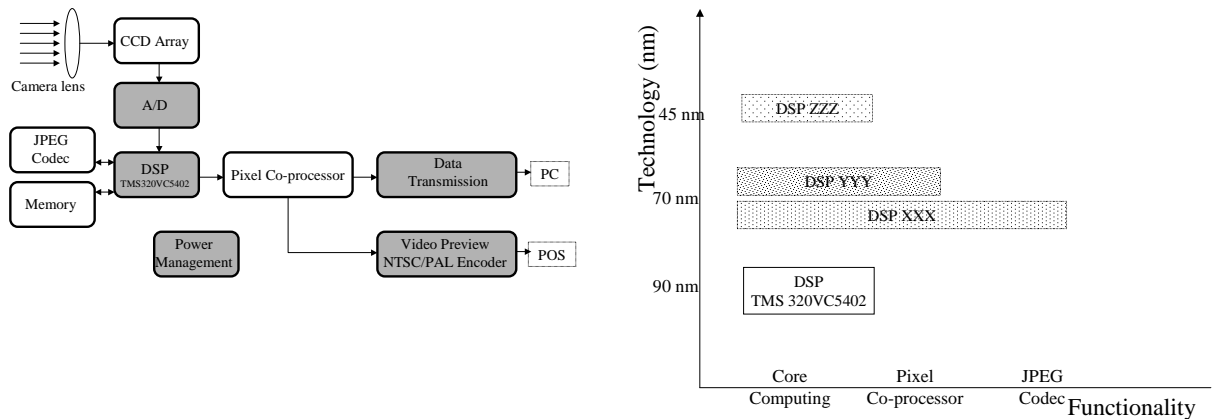


Figure 6: Example of a DSP-based Scanner

Figure on the left shows a schematic diagram of the main components of a scanner. The shaded blocks represent components that TI currently licenses. The two main subsystems are required for the operation of the scanner, namely the DSP and the pixel co-processor.

The right figure shows the potential development choices available to technology provider. TI may choose to include the pixel co-processor function in the next-generation DSP (DSP YYY and DSP XXX represent these choices), or may focus on developing a solution that offers a superior underlying technology without any functionality enhancements (DSP ZZZ).

provider is a near-monopolist with upward of 80% market-share whereas the downstream OEM market is a true oligopoly with no one OEM accounting for more than 20% market-share. Knowles has, so far, maintained the same functionality in their component and has focused solely on improving the performance (reducing the size) of the core component technology.

We adopt a multidimensional representation of component technology so as capture the two main dimensions of the development decision. The first dimension, degree of integration (i.e., what it does), refers to the amount of end-product functions offered through the component. The second dimension, improvement in the underlying technology (i.e., how well does it do it), directly impacts the performance quality associated with the component. The theoretical foundation for our approach stems from the detailed operational conceptualization of product architecture offered by Ulrich (1995). He defines the function of a product (or a part of the product such as the component in our case) as “what it does as opposed to what the physical characteristics of the product are” (Ulrich, 1995, p. 420)¹.

¹For instance, Ulrich uses the example of a trailer specifying elements such as minimize air drag, transfer load to road, suspend trailer structure etc, as its the functional elements (what we call functionality in our article).

Furthermore, he distinguishes between “the choice of functional elements [or functionality as in our article]” from “the choice of [...] features” (Ulrich, 1995, p. 434).

We examine the primary drivers for the licensing decision faced by a technology provider who licenses core components to competing OEMs, and we characterize the provider’s optimal introduction strategies with respect to both the number of OEMs to license and the mode of licensing (i.e., volume-based royalties versus fixed payments). In addition, we also offer an interesting typology of technological uncertainty based on its underlying source. This typology allows us to demonstrate that much of the conventional wisdom touting the detrimental effects of uncertainty may be applicable only to certain form of uncertainty.

We find that offering a highly integrated component has a dual effect on the technology provider’s profits. On the positive side, the provider may be able to extract larger “ease-of-use” rent from the end-product manufacturers as such components are easier to integrate (lower integration costs/risks) into the end-products. On the negative side, such highly integrated components may curtail the end-product manufacturer’s ability to differentiate from his competitors, and thus, may render such components less preferable. Thus, our results demonstrate that when a component is targeted toward a mass market (i.e., not intended for just a subset of OEMs), offering additional functionality may not be beneficial for the technology provider, and sends a cautionary message to technology providers on the potential pitfalls of “over-integration.”

In our analysis of different licensing forms, we consider licenses consisting of fixed-fees **plus** royalties and find that such mixed licenses may be optimal if the technology provider intends to license to large number of OEMs (saturation strategy). Our results offer normative support to past empirical literature findings of the prevalence of such licensing structures (e.g., see Rostoker, 1984), and stand in contrast to much of the theoretical prediction from patent licensing literature from economics that finds volume-based licenses sub-optimal.

The rest of the article is organized as follows. In §3.1 we give a brief review of the literature relating to functionality selection in component technologies and patent licensing. The model is formulated in §3.2. The two widely used licensing mechanisms in technology markets, fixed-price and volume-based royalties, are examined in §3.3.1 and §3.3.2 respectively.

§3.3.3 offers extensions to our stylized model allowing us to explore and verify the validity of our main results in much more general settings. Furthermore, the extensions also allow us to offer theoretical closure by presenting the discussion in §3.4 about (i) some of the empirical implications of our results, and (ii) the reasons why firms may choose one component development strategy over another (for example, Intel has chosen the “integration-driven” approach whereas Knowles pursues a “performance-driven” component development).

3.1 Literature Review

Three main areas in the academic literature have explored different aspects of our research question: (i) the new product development (NPD) literature, (ii) the engineering design literature, and (iii) the patent-licensing literature from economics. A brief review of each of these is offered next.

Product Architecture in NPD: Ulrich defines the product architecture as “the scheme by which the function of a product is allocated to its physical components” (Ulrich, 1995, p. 419). Based on this definition, he proposed an influential conceptual framework for classifying product architectures. Following Ulrich, we use the term *functionality* or functional elements of an end-product (or its sub-parts) to refer to “what it does” (Ulrich, 1995, p. 420). Figure 7 illustrates the conceptual framework for a typical product composed of multiple components.

Operations management literature has examined the impact of different product architectures on operational variables such as flexibility, efficiency, profitability, and re-usability. Baiman et al. (2001) examine the impact of product architecture on supply chain performance metrics when each link in the supply chain produces a separate component. Krishnan and Gupta (2001) and Dana (2003) examine the economic value of having multiple product groups based on common platforms. Krishnan and Ramachandran (2004) analyze a monopolist selling design-intensive products (i.e., products where the fixed development cost outweighs the variable cost of manufacturing) to rational end-product customers. They find that architectural decisions (specifically, decisions to split a product into modules) can reduce customer regret and enable the monopolist to maintain a credible price-discrimination

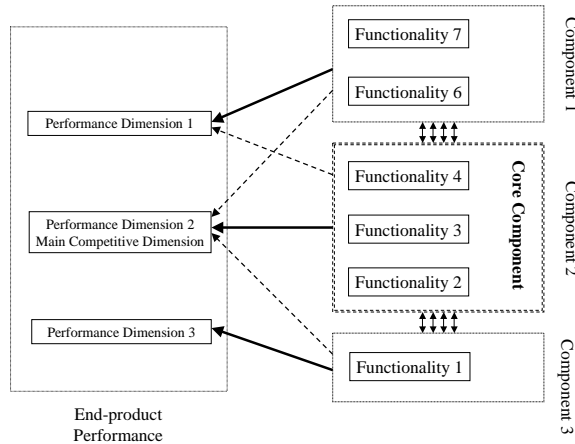


Figure 7: Conceptual Framework of Product Architecture (adapted from Ulrich, 1995) The core-component (component 2 in the figure) encapsulates a set of functionalities (functionality 2,3, and 4) and impact the main competitive dimension (dimension 2) of end-product performance.

strategy. Erat and Kavadias (2005) examine the effect of improving technologies on a technology providers introduction decisions. They find that when technology improves in small increments it may be beneficial for the provider to induce a slow diffusion pattern and allow only a limited number of OEMs to adopt in any period. However, they do not account for the architectural choices (i.e., decision on functionality set) and limit their analysis to technology provider’s inter-temporal licensing strategies.

This stream of literature examines the effect of architecture choice in the context of a single firm. Our emphasis, on the other hand, lies in examining decentralized business contexts where the architectural decisions (i.e., choice of the set of functionalities and/or the underlying technology of the component) are made by one firm (technology provider) whereas the actual end-product manufacturing/assembly is performed by other firms.

Engineering Design: A large body of literature in the domain of engineering design has examined the product architecture question. Pimmler and Eppinger (1994) describe a normative approach to the architecture design problem; they use a matrix based formulation and solve for the optimal allocation of functions to the components. Stone et al. (2000) develop a heuristic solution for the task of identifying modules from functional descriptions (i.e., functionalities). Blackenfelt (2000) demonstrates a solution method for the problem

of optimally allocating functionality between components. The heuristic involves two different techniques: the Design Structure Matrix (see Eppinger et al., 1994) and the Modular Function Deployment (see Gunnar, 1998).

In contrast to the focus of our study, the techniques (heuristics) found in this stream of literature have been primarily tactical in nature, and have dealt with the issue of modularization and architecture design without taking into account any strategic value derived from the allocation scheme.

Patent Licensing: Since the pioneering work of Arrow (1962) examining the licensing of cost-reducing innovations, a number of economists have studied when and how innovations (patents or Intellectual Property rights) are licensed (Kamien and Tauman, 1984; Katz and Shapiro, 1985). The dominant approach has been to consider an R&D firm who licenses cost reducing innovations to firms competing *à la* Cournot. Thus, in this stream of literature, technology is viewed as unidimensional with a single parameter (cost or performance) characterizing it. For an extended survey of this stream of literature, see Kamien (1992).

One of the main findings from this stream may be summarized as follows: Volume-based royalties (i) alleviate two-sided moral hazard, and (ii) share innovation risk optimally between risk averse agents (see Martin, 1988; Holmstrom and Milgrom, 1987). In the case of risk neutral agents with complete information (i.e., no private information), Kamien and Tauman (1986) show that volume-based royalties are in general inferior to fixed-price licenses.

Empirical studies of patent licensing are few and limited, mainly due to the difficulties in obtaining detailed contract data. However, the few available studies (e.g., see Rostoker, 1984) do observe that volume-based royalty is an element of most licensing agreements despite the theoretical prediction of their sub-optimality. For instance, Rostoker (1984) finds that the fixed-price **plus** volume royalty is the most frequently used (46%), followed by pure volume-based royalties (39%).

Despite the empirical observation of the prevalence of mixed licensing mechanisms that include fixed-fees and volume-based royalty, most past literature has focused on either fixed-price contracts, or on volume-based royalties, and on comparing between them (see Kamien,

1992). With a few exceptions (e.g., Kamien and Tauman, 1984), this stream of research has mostly disregarded the possibility of combining the two mechanisms together. We explicitly consider such mixed licensing arrangements. Furthermore, instead of focusing on any one specific competition mechanism among the licensees (such as the Cournot competition assumption common in much of patent licensing literature), we consider a generic competition mechanism so that our results are generalizable. Lastly, unlike past studies on technology licensing, we view component technologies as multidimensional and as being characterized not only by how well they performs (i.e., the underlying performance characteristics), but also by what they do (i.e., the functionality it provides).

3.2 *Model Setup*

Consider a monopolist technology provider who offers a component technology \bar{C} for licensing to n OEMs. For mathematical tractability, we assume a duopoly in the downstream market, i.e., $n = 2$.

The component licensed by the provider is one of the many components that comprise the end-product. Hence, the OEMs undertake further integration/development of the remaining components to obtain a fully functional end-product. For example, Nokia, after acquiring TI's generic DSP, integrates it with additional components to develop a working cell-phone.

The component \bar{C} is represented by the tuple $[f, T]$, where f is the fraction of end-product functionality that \bar{C} offers, and T is the underlying technology utilized in \bar{C} ². We assume that the end-product “performance”³ of the end-product is determined by the underlying technology utilized in the (core) component, i.e., performance of the end-product $P(T)$ is an increasing function of T . Without loss of generality⁴, let $P(T) = T$.

²In the context of PC desktops, suppose that the main functionalities are core computing, wireless, and multimedia support. If the component \bar{C} provides the core computing and the wireless functionality, then $f = \frac{2}{3}$. The underlying technology T may be 90 nm or 40 nm.

³We define the “performance” in terms of the major competitive dimensions of the end-product market. For instance, if the cost is the basis for competition, then “performance” denotes manufacturing costs, alternatively if it is quality-based competition, then “performance” refers to performance quality.

⁴Note that the assumption of linear relationship between P and T , i.e., $P = T$, entails no loss of generality. Even if the performance $P = P'(T')$ where $P'(\cdot)$ is an increasing function, then, by normalizing the technology T as $T \equiv P'(T')$, we obtain $P = T$. Intuitively, the technology may be measured in terms of

Once an OEM adopts the component technology \bar{C} , he⁵ undertakes integration. However, the outcome of the integration process is uncertain. This uncertainty stems from one of the following two sources: (i) component specific uncertainty due to the novelty of the underlying technology, and (ii) uncertainty arising from the OEM’s integration processes. The former is component-specific and *systemic* in nature, i.e., it is common across the users of the component and is independent of the individual OEM’s integration processes. The latter, on the other hand, is OEM-specific and *idiosyncratic* in nature, and depends on the specific ancillary components that an OEM uses as well as the complexity of his integration process.

From an empirical standpoint, it may be difficult to quantify the contribution of these uncertainties. We offer an analogy that clarifies the distinction between them and suggests a concrete way of quantifying the two proposed forms of uncertainties: Consider the outcomes, success versus failure, associated with usage of a specific drug. The probability of success may depend on (a) the dosage, and (b) the patient’s genetic predisposition or medical history. The former is analogous to the systemic component-specific uncertainty of our context whereas the latter relates to the idiosyncratic agent-specific and/or integration process uncertainty. Furthermore, the relative contributions of the two types of uncertainties may be estimated using design of experiments techniques (e.g., see Fedorov and Leonov, 2001).

Based on this typology of uncertainty, we model the overall uncertainty as follows: Let $p_I(f)$ be the probability that the integration is successful given a perfectly performing component, and let $p_C(T)$ be the uncertainty associated with the specific component. Then, $p_C(T)p_I(f)$ is the overall probability that the integration is successful. We assume that the OEM’s incur an integration process cost $C(f, T)$ ⁶.

A higher fraction of unique components (i.e., lower f) and the associated engineering

its impact on performance.

⁵For ease of exposition we refer to OEMs as ‘he’ and the technology provider as ‘she.’

⁶These probabilities and costs are assumed to be common knowledge. Asymmetric information and/or private knowledge may induce signalling effects. However, since our focus lies in characterizing the main effects, we abstract away from such informational asymmetries and leave their consideration for future research.

work create a complex planning process that requires more time and resources to complete (Clark, 1989), and may impair the OEM's ability to accurately judge the component interactions and integration risks (Schilling, 2000). Furthermore, both the costs and the uncertainty associated with integration are likely to increase super-linearly with number of components that are being integrated due to the possibility of exponential number of interactions⁷. Thus, we assume that

A0.1: $p_I(f)$ is increasing concave in f

A0.2: $C(f, T)$ is decreasing concave in f

The novelty of the underlying technology may substantially increase the uncertainty and the integration costs associated with a component:

A0.3: $p_C(T)$ is decreasing convex in T

A0.4: $C(\cdot, T)$ is increasing convex in T .

We assume that the OEMs compete in a common end-product market and that the end-product performance is a key determinant of this competition. Let $\Pi(P_i, P_j)$ be the payoff to OEM i ($i = 1, 2$) when his end-product has performance P_i and his competitor j 's ($j = |3 - i|$) end-product has performances P_j .

Our proposed model of competition, i.e., the payoff function $\Pi(\cdot, \cdot)$ is general enough to include the possibility that the OEMs employ additional levers to manage the competition. For instance, suppose that the OEMs also have the ability to add extra features (which are distinct from our definition of functionality) and engage in price competition. Let $\Phi(P_i, P_j, \lambda_i, \lambda_j, w_i, w_j)$ be the payoff to OEM i ($i = 1, 2$) when his end-product performance is P_i , extra features in his end-product is λ_i , and his price is w_i , and his competitor j 's ($j = |3 - i|$) end-product performance, features, and price are P_j , λ_j , and w_j respectively. Then, $\Pi(P_i, P_j)$ is the Nash-Equilibrium outcome of the features selection + pricing game, i.e., $\Pi(P_i, P_j) \equiv \Phi(P_i, P_j, \lambda_i^*, \lambda_j^*, w_i^*, w_j^*)$ where w_i^*, λ_i^* is such that

⁷Intuitively, the costs and the uncertainty for integrating $2m$ components are likely to be more than twice the cost and uncertainty when integrating m components.

$\Phi(P_i, P_j, \lambda_i^*, \lambda_j^*, w_i^*, w_j^*) \geq \Phi(P_i, P_j, \lambda_i, \lambda_j, w_i, w_j)$ for $i = 1, 2$. Note that we implicitly assume that component adoption occurs first followed by the competition between the OEMs, and that the Nash-equilibrium of the features selection + pricing game is unique.

The structure of the profit function $\Pi(\cdot, \cdot)$ subsumes the market (or competition) mechanism that allocates profits to the OEMs. Instead of assuming a specific market mechanism (such as the Cournot or the differentiated Bertrand competition setting), we adopt an axiomatic approach to modelling competition between OEMs and assume a set of intuitive and fundamental properties that a general market mechanism satisfies. In Appendix B, we demonstrate that the properties assumed for the market mechanism are indeed general, and are satisfied by a wide variety of economic models of competition such as differentiated Bertrand and competitive Logit models frequently employed in Marketing literature. Thus, our axiomatic approach to modelling competition allows for greater generalizability of our results.

The assumptions imposed on the competition mechanism $\Pi(\cdot, \cdot)$ are given next.

A1: $\Pi(P_i, P_j)$ is increasing and concave in P_i . That is, $\frac{\partial \Pi}{\partial P_i} > 0$ and $\frac{\partial^2 \Pi}{\partial P_i^2} < 0$.

Intuitively, greater end-product performance leads to greater profits, however, the rate at which the profits increase is decreasing (i.e., the performance exhibit decreasing marginal returns).

A2: $\Pi(P_i, P_j)$ is decreasing and convex in P_j . That is, $\frac{\partial \Pi}{\partial P_j} < 0$ and $\frac{\partial^2 \Pi}{\partial P_j^2} > 0$.

Intuitively, an OEM's own profits would decrease when his competitor's end-product has superior performance. Furthermore, this decrease in profits is likely to be greater when the competitor's performance is only marginally superior⁸.

A3: $\Pi(P'_i, P_j) - \Pi(P_i, P_j)$ is decreasing in P_j for all $P'_i > P_i$. That is, $\frac{\partial^2 \Pi}{\partial P_i \partial P_j} < 0$.

The performances are weak “substitutes” (i.e., $\Pi(P_i, P_j)$ is *submodular* in (P_i, P_j) , see Topkis, 1978, for more on submodular functions and their properties). Intuitively, the benefit from a achieving a superior performance is greater if the competitor lags significantly

⁸For example, suppose an OEM's end-product performance was 1, and his competitor switches from an end-product of performance 1 to performance 2. Compare this to the situation where his competitor switches from end-product of performance 100 to performance 101. The convexity assumption implies that the decrease in profits is the first case (competitor switching from 1 to 2) is likely to be more than the decrease in profits in the second case (competitor switching from 100 to 101).

in performance. As an example, consider the case where Seagate uses TI's superior DSP and Maxtor switches from using their own low performance solution to TI's DSP solution. Contrast this with the case where Seagate is using a low-performance solution and Maxtor switches to TI's DSP solution. The benefits would be smaller in the former case than in the latter.

We normalize the performance of end-products offered currently (i.e., before any adoption decisions) to 1. For ease of notation, let (i) $a(T) = \Pi(P(T), P(T))$, (ii) $b(T) = \Pi(P(T), 1)$, (iii) $c(T) = \Pi(1, P(T))$ (iv) $d = \Pi(1, 1)$, and let $S(T) = a(T) - c(T)$, and $F(T) = b(T) - d$. Thus, $S(T)$ ($F(T)$) represents the incremental benefit of the component licensee when his competitor uses (does not use) the same superior technology. Finally, we make the following structural assumption of the market mechanism for consistency with assumptions **A1-A3**.

A4: $F(T) - S(T)$ is increasing and convex in T .⁹

Assumption **A4** states that the relative benefits are increasing in the technology and that rate of increase is increasing as well. The convexity assumption, though useful in terms of allowing mathematical tractability, is relatively unimportant for the validity of our main results as we demonstrate through numerical examples.

The sequence and timing of decisions in the adoption game proceeds as follows. In the first stage the technology provider introduces the technology $\bar{C} = [f, T]$ and sets the license fees at \bar{W} . The license fee $\bar{W} = [W, w]$ is composed of two parts, a fixed one-time payment, W , paid for the adoption, and a per-unit royalty w , paid for each unit of end-product sold. After the license fee has been announced the OEMs decide, based on their resultant profits, whether or not to adopt the technology. Upon adoption the OEMs undertake integration of the newly acquired component technology into their end-product at cost $C(f, T)$ and are successful with probability $p_C(T)p_I(f)$. In case of success, the adopting OEM utilizes the

⁹Note that the assumption that $F(T) - S(T)$ is decreasing for all T is inconsistent with assumptions **A1-A3** as the following argument shows - Suppose, $F(T) - S(T)$ is decreasing for all T . By **A1** we know that $F(0) - S(0) = 0$. Furthermore, by **A3** we know that $F(T) - S(T) \geq 0$. However, we have assumed that $F(T) - S(T)$ is decreasing, and thus we have a contradiction. Thus, $F(T) - S(T)$ cannot be decreasing for all T . However, assumption **A4** is not redundant since it is possible that $F(T) - S(T)$ is increasing for some T and decreasing for others.

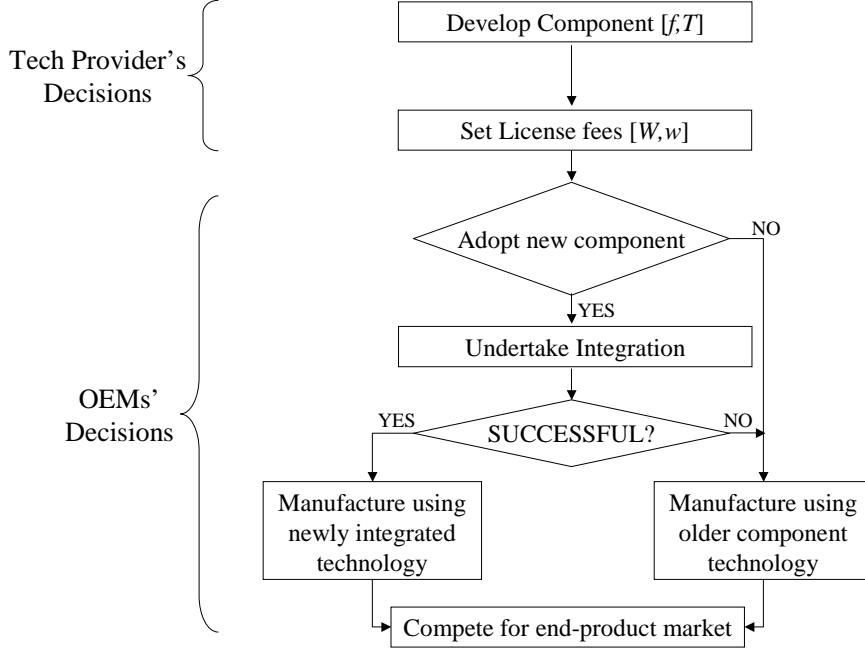


Figure 8: Timeline of decisions

newly integrated component in their end-products whereas the older component is employed in their end-product in case of failure. The end-products are then competitively sold and revenue is accrued by the OEMs.

3.3 *Optimal Licensing Policy*

This section examines the optimal licensing strategies. §3.3.1 addresses the case of fixed one-time payment only (i.e., $w = 0$) and the case of volume-based royalties plus a fixed one-time payment is considered in §3.3.2. §3.3.3 extends the basic setup to address the impact of heterogeneous integration capabilities among OEMs and of the complexity/standardization of end-product architectures on the provider's optimal licensing strategies.

3.3.1 **Fixed Payment**

We consider the case where the technology is licensed for a life-time fee (i.e., $W > 0$ and $w = 0$). This model reflects industrial settings where the actual component may be manufactured by the OEMs themselves and only the Intellectual Property (IP) rights are transferred from the technology provider to the OEMs for a life-time usage fee.

Before proceeding further, we offer the following definitions to facilitate the explanation of the intuition behind our subsequent results.

Definition 1: Even if both OEMs adopt the new component and undertake integration, there is a chance that their individual integration outcomes are different and their end-products are differentiated in terms of performance. Define the degree of potential differentiation (if both adopt the same component) as the probability that the integration outcomes are different:

$$\text{Degree of Potential Differentiation} = 2p_C p_I (1 - p_I)$$

Definition 2: An introduction strategy where the technology provider sets license fees such that

- all the OEMs attempt integration is termed a *saturation* strategy.
- only a subset of the OEMs attempt integration is termed a *niche* strategy.

Proposition 9 describes the (optimal) license fee that the provider charges contingent on the particular introduction strategy she pursues.

Proposition 9 *The technology provider optimally employs the saturation strategy by setting the license fee $W = W_s - C$ where*

$$W_s = p_C (p_I (b - d) - p_I^2 ((b - d) - (a - c)))$$

or she may optimally pursue the niche strategy by setting the license fee $W = W_n - C$ where

$$W_n = p_C p_I (b - d)$$

The corresponding technology provider revenues are $\pi_s = 2(W_s - C)$ and $\pi_n = W_n - C$. The overall optimal introduction strategy is determined by which of these two strategies generate higher provider revenues.

Proposition 9 reveals an interesting insight: The technology provider's revenues decrease with systemic uncertainty (i.e., π_s is increasing in p_C). However, the provider revenues, when employing the saturation strategy, may increase with the idiosyncratic uncertainty

(i.e., π_s may decrease with p_I). The differing impact of the two forms of uncertainty is explained as follows: With lower idiosyncratic (integration) uncertainty, the fate of each OEMs integration effort depends more on the component uncertainty. Hence, the potential for a differentiated outcome is smaller with lower idiosyncratic uncertainty. Furthermore, with lower potential for differentiation, it becomes less likely that any one OEM obtains highest possible “monopolist” profits ($= b(T)$). Thus, the lower potential differentiation leads to the OEMs paying less for the component technology and consequently to lower revenues for the provider. Lower systemic (component) uncertainty, on the other hand, benefits the OEMs (and thus the provider) by increasing the potential differentiation. The insight is summarized in the following corollary.

Corollary 2 *The provider revenues under saturation strategy may decrease in f .*

Corollary 2 offers an important managerial insight. While offering greater integration and enhancing the “ease-of-use” of the component (increasing p_C) seems to be a viable value creation strategy, such an approach need not always be beneficial, since the strategy also has the indirect effect of diminishing the differentiation and increasing the competition between OEMs. Thus, the latter indirect effect should also be accounted when a technology firm embarks on a strategy of offering highly integrated, easy-to-use components.

Theorem 2 characterizes the provider’s strategy as a function of the functionality f and underlying technology T of the component.

Theorem 2

- *There exist thresholds $0 \leq f_0(T) \leq f_1(T) \leq f_2(T) \leq 1$ such that the provider finds it optimal to (i) undertake the niche strategy if $f \in [f_0, f_1]$ or $f \in [f_2, 1]$, (ii) undertake the saturation strategy if $f \in [f_1, f_2]$, and (iii) not to license to any of the OEMs if $f \in [0, f_0]$.*
- *There exist thresholds $1 \leq T_0(f) \leq T_1(f) \leq T_2(f)$ such that the provider finds it optimal to (i) undertake the niche strategy if $T \in [T_0, T_1]$ or $T \in [T_2, \infty)$, (ii) undertake the saturation strategy if $T \in [T_1, T_2]$, and (iii) not to license to any of the OEMs if $T \in [1, T_0]$.*

As the component offers superior performance through its underlying technology or provides greater functionality, the provider finds it optimal to license to more OEMs. However, for highly-integrated components, any adopting OEM can successfully integrate the component into their end-product. Due to this, the potential differentiation between the OEMs decreases causing the competition between them to increase, thus diluting the overall value the provider may obtain by licensing to a large number of OEMs. Consequently, the provider focuses on fewer OEMs when offering a highly integrated component so as to prevent the downstream competition from increasing too much. Similarly, for drastic innovations, i.e., $T \gg 1$, an adopting OEM can become a monopolist and drive his competitors out of the market. Thus, the provider licenses to only one OEM obtaining all the revenues from a single OEM.

Proposition 10 characterizes the behavior of the thresholds and allows us to analytically derive the shape and structure of different regions contingent on the component technology.

Proposition 10

- *The thresholds $f_0(T), f_1(T), f_2(T)$ are non-increasing in T .*
- *The thresholds $T_0(f), T_1(f), T_2(f)$ are non-increasing in f .*

Figure 9 illustrates the technology providers' optimal strategies as a function of the component $[f, T]$. The regions are plotted for a specific profit function $\Pi(P(T_1), P(T_2)) = T_1^{(0.6)}T_2^{(-0.3)}$, costs $C(f, T) = 0.8(1-f)$, and probability of success $p_I(f) = f^{(0.9)}$, $p_C(T) = 1$.

3.3.2 Fixed-fees plus Royalties

In §3.3.1 we assumed that the component technology is licensed for a fixed one-time payment. This allowed us to abstract away from the complex licensing arrangements often found in practice and to isolate the effect of the two main development levers available to the technology provider, i.e., functionality and underlying technology, on her optimal introduction strategy. However, observations from actual technology markets suggest that many component technology providers utilize volume-based fees (royalties) in addition to the

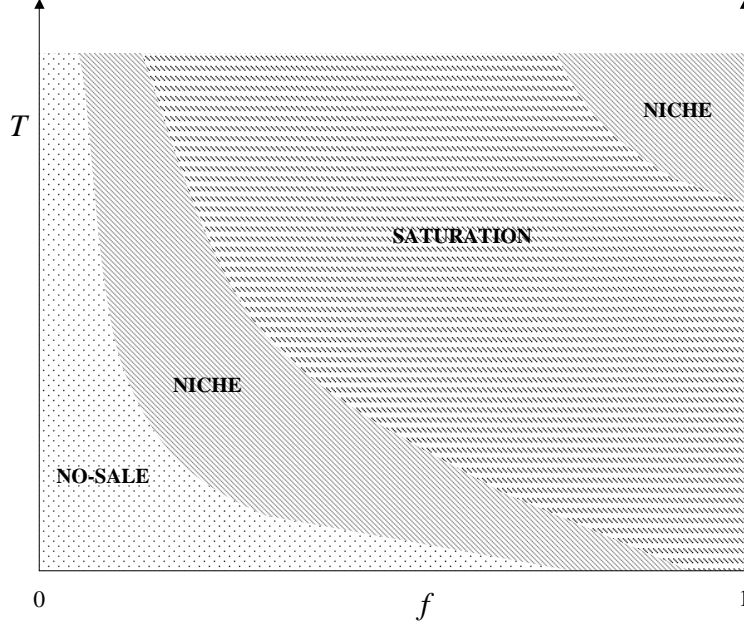


Figure 9: Optimality Regions without volume-based fees

fixed usage fees (Rostoker, 1984). In this section, we consider richer licensing structures, and examine the impact of the same operational variables, functionality and underlying technology, on the provider’s optimal choice of the licensing mechanism.

Consider the general license fee structure $\bar{W} = [W, w]$ where W is the fixed-price component and w the per-unit price. Our notation is adjusted to address the case of volume-based royalties. The payoffs $\Pi(\cdot, \cdot)$ may now also depend on the per-unit license-fee charged. The payoffs may depend on the per-unit license-fee charged since the per-unit fee w , unlike the fixed-price W (a sunk-cost after adoption), represents (at least part of) the per-unit cost. Hence, the OEM may increase/decrease the total cost incurred by increasing/decreasing the volume produced.

An OEM faces demand (i) D_a when both he and his competitor have integrated the component into their end-products, (ii) D_b when he has integrated the component into his end-product whereas his competitor has not, (iii) D_c when he does not have the component and his competitor does, and finally (iv) D_d when both he and his competitor do not utilize the new component.¹⁰

¹⁰Note that the demands D_a, D_b, D_c depend on w, T .

Let $a(T, w)$, $b(T, w)$, $c(T, w)$, and d be the revenues when the per-unit price of w is charged. Hence, an OEM's net payoffs when both are successful in integration is $a(T, w) - D_a w$. Similarly, the net payoffs for the other three cases are $b(T, w) - D_b w$, $c(T, w)$ and d respectively. Also, as before, let $F(T, w) = b(T, w) - d$ and $S(T, w) = a(T, w) - c(T, w)$ represent the increase in OEM revenues upon adoption contingent on his competitor's adoption decision.

Finally, we make the following intuitive assumptions about the impact of the royalty fee w on the OEM payoffs.

A5.1 $b(T, w)$ is decreasing in w . That is, $\frac{\partial b}{\partial w} < 0$.

A5.2 $c(T, w)$ is increasing in w . That is, $\frac{\partial c}{\partial w} > 0$.

A5.3 $a(T, w)$ is concave in w . That is, $\frac{\partial^2 a}{\partial w^2} \leq 0$.

Paying a higher royalty fee is likely to reduce the OEM's payoff since it increases the variable cost of his end-product and leads to either lower margins or higher prices with lower sales. In contrast, when the competitor pays higher royalty, the OEM's own payoffs are likely to increase.

The effect of the royalties on the revenues is less clear when both OEMs adopt. For very high royalties (i.e., high effective variable costs), it is likely that the each OEM's demand diminishes (irrespective of competitor's costs), as the customers would not buy the end-product even if priced at cost thus leading to lower payoffs. However, when the royalty is low, it is likely that small increases of royalty may actually lead to increases in payoffs. As an example, suppose the OEMs are Bertrand competitors and that the variable cost and the royalty for the end-product are 0. The competition between the OEMs is likely to be intense and result in low (near-zero) payoffs. However, if the royalty is increased to ϵ , the OEMs cannot price lower than the per-unit-cost ϵ , thus leading to higher payoffs ($= \epsilon \times \frac{\text{market-size}}{2}$). Thus, we make the assumption that the payoffs are concave in the industry costs (i.e., potentially increasing initially, but ultimately decreasing).

Propositions 11 characterizes the type of license the technology provider offers so as to induce a particular adoption equilibria.

Proposition 11

(A) A license fee $\bar{W} = [W, w]$ induces a saturation strategy iff

$$p_C (p_I^2 D_a w + p_I (1 - p_I) D_b w) + W \leq p_C (p_I F(w) - p_I^2 (F(w) - S(w))) - C$$

or it induces a niche strategy if

$$p_C p_I D_b w + W \leq p_C p_I F(w) - C$$

(B) The optimal profits if the provider uses the saturation strategy is

$$\pi_s = 2 \left(p_C p_I \left(\max_{w \geq 0} \{ (1 - p_I) F(w) + p_I S(w) \} \right) - C \right)$$

and her optimal profits if she uses the niche strategy is

$$\pi_n = p_C p_I F(w = 0) - C$$

Proposition 11 reveals an interesting insight into the problem structure: the actual demand does not appear in the provider's profit function. Intuitively, the volume-based royalty allows the provider to appropriate the entire increase in revenues. Thus, the dependence of demand on providers profit is only through its effect on the total revenues. Furthermore, the profits under the two strategies retain the same structure as in the fixed-payment case. The following corollary characterizes the conditions under which the different licensing schemes are optimal.

Corollary 3 *A one-time licensing fee is optimal when the technology provider undertakes the niche-strategy. However, when the technology provider undertakes the saturation strategy, she may charge a royalty $w > 0$ in addition to the fixed-price.*

Thus, a licensing scheme with only fixed-prices is optimal under the niche-strategy. Volume-based licenses, on the other hand, is desirable only when the component is intended for multiple OEMs. Intuitively, volume-based royalties when used together with saturation strategy artificially inflates the per-unit cost for the entire industry (i.e., for all

the OEMs) and potentially increases the total industry revenues (i.e., sum of revenues of all the OEMs $=a(T, w) + a(T, w)$). Furthermore, the fixed-fee allows the technology provider to appropriate this revenue increase. However, when employing the niche strategy, the familiar phenomenon of double marginalization results in the revenues decreasing as the royalty (per-unit cost) increases, thus deterring the provider from employing a volume-based licensing mechanism. The insight bears significant managerial implication: the technology provider may use the additional lever of volume-based royalties to manage the level of inter-firm competition and control the licensees' revenues. Therefore, the appropriate choice of the licensing mechanism requires an understanding of the extent and intensity of competition among the OEMs.

In the complete information case with risk neutral agents, Kamien and Tauman (1986) find that licensing based on volume-based royalties is in general inferior compared to fixed-price contracts. Economists have proposed two reasons - moral hazard issues with asymmetric information and optimal sharing of risk between risk-averse agents - to justify incentive contracts (like royalty contracts) in technology licensing. In addition to these compelling justifications for the existence of royalty-based contracts, our results allow us to propose an additional reason: royalty-based contracts allow the technology provider to modify and moderate the competition between the adopting OEMs. Furthermore, our results demonstrate that weakening two common assumptions in licensing literature (Cournot competition between OEMs, and contract structures with only one type of licenses) alters the results significantly, and that in some cases, the combination of volume-based licensing and fixed-fees does indeed generate more revenue than fixed-fees alone. Thus, our results demonstrate that the two mechanisms, volume-based royalties and fixed-fees, are not substitutes and serve complementary functions, with volume-based royalties being used for managing competition between licensees and controlling the licensees' revenues and fixed-fees being used in appropriating these revenues.

Theorem 3 extends Theorem 2 to the case where the provider uses volume-based royalties in addition to a fixed one-time fee. Also, Proposition 12 analytically characterizes the shape of the different optimality regions by obtaining threshold sensitivity results.

Theorem 3

- *There exists thresholds $0 \leq f_0(T) \leq f_1(T) \leq f_2(T) \leq 1$ such that the provider finds it optimal to (i) undertake the niche strategy iff $f \in [f_0, f_1]$ or $f \in [f_2, 1]$, (ii) undertake the saturation strategy iff $f \in [f_1, f_2]$, and (iii) not license to any of the OEMs iff $f \in [0, f_0]$.*
- *There exists thresholds $1 \leq T_0(f) \leq T_1(f) \leq T_2(f)$ such that the provider finds it optimal to (i) undertake the niche strategy iff $T \in [T_0, T_1]$ or $T \in [T_2, \infty)$, (ii) undertake the saturation strategy iff $T \in [T_1, T_2]$, and (iii) not license to any of the OEMs iff $T \in [1, T_0]$.*

Proposition 12

- *The thresholds $f_0(T), f_1(T), f_2(T)$ are non-increasing in T .*
- *The thresholds $T_0(f), T_1(f), T_2(f)$ are non-increasing in f .*

The optimal strategy (i.e., saturation vs. niche) retains the same structure as in the case of only fixed one-time license fees. The discussion and the intuition mirror those offered for Theorem 2 and Proposition 10.

The next proposition characterizes the dependence of royalty on the functionality f of the component.

Proposition 13 *There exists a threshold $f_v(T)$ such that volume-based royalties are optimal iff $f \geq f_v(T)$.*

Past literature suggests that the value of royalty contracts comes from their ability to provide incentive/contingent licensing agreements (e.g., see Kamien and Tauman, 1984). That is, by using the royalty contracts, the provider reduces the risk to the OEMs since they have to pay only upon successful integration. Our results indicate that royalty-fee is present only when integration risk is low ($w > 0$ when $p_I(f) > p_I(f_v(T))$). Thus, our results suggest that, in the case of risk-neutral agents (as in our model), volume-based royalty fee

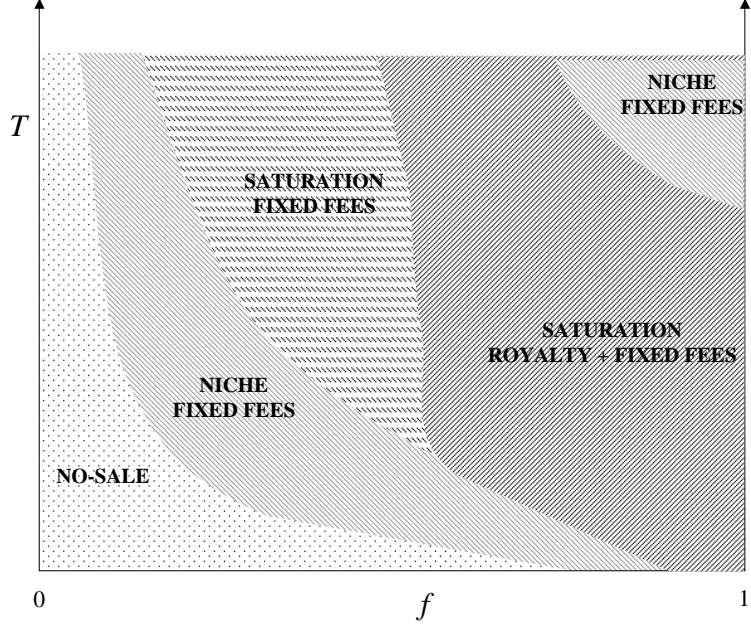


Figure 10: Regions when licensing may also include volume-based royalties

may still be appropriate even when integration risk is low since such fees may serve to moderate the competition between the OEMs.

Our previous results (Corollary 3, Proposition 13, Theorem 3 and Proposition 12) allow us to construct optimality regions, shown in figure 10, for the optimal licensing strategy.

3.3.3 Impact of Other Product and Market Specific Variables

We have assumed so far that the complexity of the (architectural) interfaces in the end-product is exogeneously specified. Furthermore, the OEMs and their integration capabilities are identical. In this section, we explicitly revisit these assumptions and address the impact of these product and market specific variables on the optimal licensing strategies. Due to the additional analytical complexity introduced by accounting for these extensions we shall restrict attention only to the case of fixed license-fees (i.e., throughout this section we assume that $w = 0$).

Product integration is likely to exhibit lower uncertainty when the product architecture is mature and its interfaces are standardized. We let K proxy the complexity of the interfaces and assume that the probability of success from the integration effort is $p_I(f, K)$; with $p_I(f, K)$ is decreasing in K . Furthermore, we assume that $p_I(f, K)$ is submodular in

(f, K) (i.e., $\frac{\partial p_I}{\partial f \partial K} \leq 0$). Intuitively, the effect of architectural complexity is lesser on highly integrated components compared to less integrated components¹¹.

In similar vein, the heterogeneity in (integration) capabilities of the OEMs is proxied through a cost differential parameter κ . Let the integration cost for OEM 1 be $C(f, T) - \kappa$, and for OEM 2 be $C(f, T) + \kappa$.

Propositions 14 and 15 address the effect of architectural complexity and heterogeneity in capabilities.

Proposition 14

Greater product architecture complexity K leads to

- *larger no-sale region*
- *smaller niche region.*
- *larger saturation region*

Intuitively, as interfaces become more standardized (i.e., architectural complexity K is low), the technology provider is able to introduce lower functionality component (involving greater OEM integration) and still gain positive revenues. Thus, the no-sale region diminishes.

When the interfaces becomes more standardized or equivalently when the probability of integration becomes high for both OEMs ($p_I \approx 1$), the differentiation potential ($= 2p_C p_I (1 - p_I)$) becomes low. Hence, the OEMs perceive a lower potential for differentiation, and thus lower chances of accruing high (monopolist) profits. As the reaction, the provider realizes less value in licensing to large number of OEMs. Therefore, more standardized architectural interfaces (i.e., lower architectural complexity K) leads to the saturation-strategy region diminishing and the niche-strategy region increasing.

¹¹The assumption of submodularity is a relatively weak one. For instance, it is satisfied if the function is multiplicative, i.e., $p_I(f, K) = p_I(f)g(K)$ where $g(K)$ is a decreasing function.

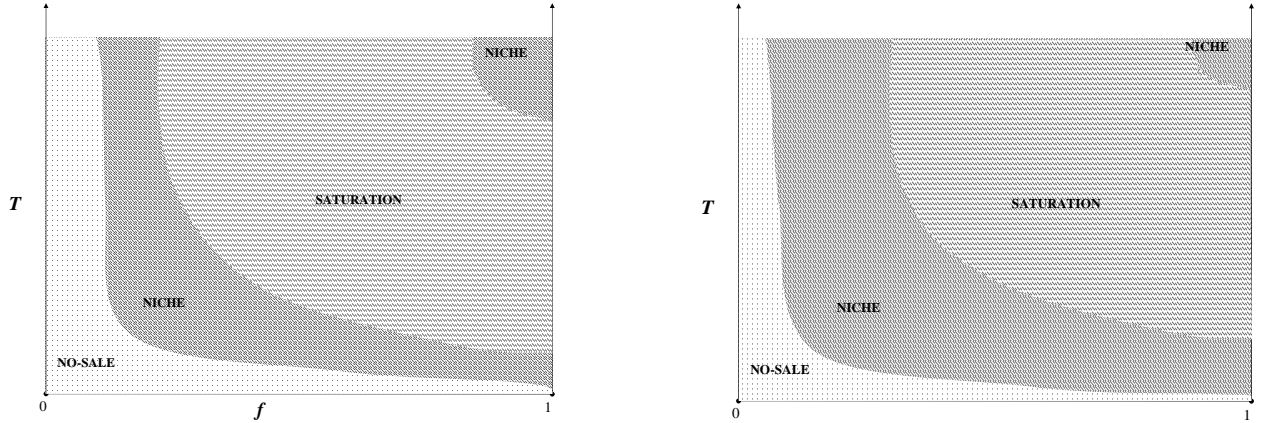


Figure 11: Changes in Optimality Regions with decrease in architectural complexity
 Figure on the left shows the regions for a specific architectural complexity K . The right figure shows the changes in the regions when the architectural complexity is $K' (< K)$. As can be observed, the saturation-region shifts right, but also shrinks; the no-sale region shrinks; and the niche-region becomes larger.

Proposition 15

Greater heterogeneity of OEM capabilities κ leads to

- *smaller no-sale region.*
- *larger niche region.*
- *smaller saturation region.*

Intuitively, if the OEM capabilities are more heterogeneous, the provider is able to assure herself of revenues even upon introducing a more difficult to integrate component (i.e., component requiring more costly integration) since the more capable OEM can still profitably use the component. Thus, the no-sale region diminishes.

Similarly, as the OEMs become more heterogeneous, the provider finds saturation strategy less appealing as it requires her to price the component lower so as to be adopted even by the lower capability OEM. Thus, more heterogeneous OEM market lead to niche-region becoming larger and saturation-region diminishing.

The insights from Propositions 14 and 15 are summarized in Figures 11 and 12. These insights are relevant from the descriptive standpoint in allowing us to understand and explain the differences in licensing strategies in terms of product and market related characteristics.

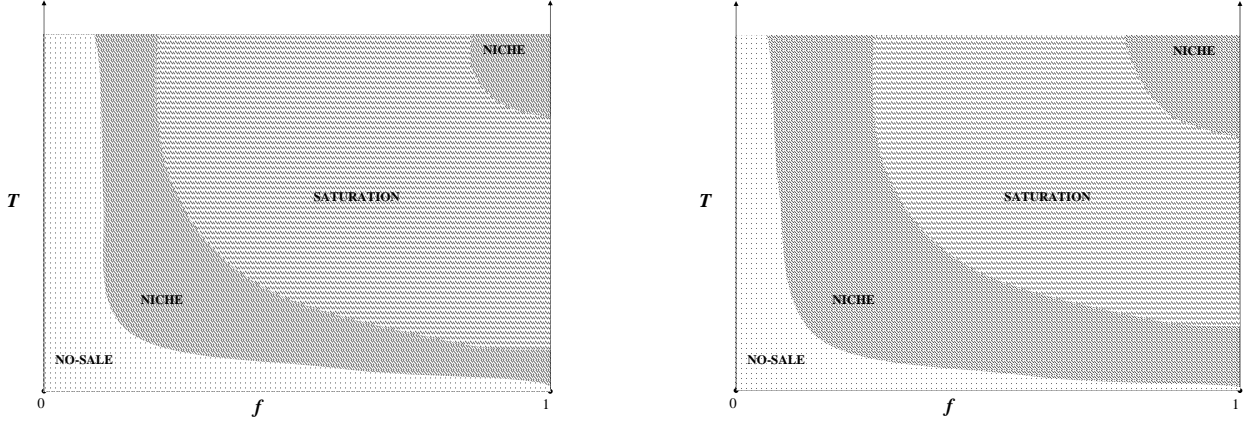


Figure 12: Changes in Optimality Regions with increase in OEM heterogeneity
 Figure on the left shows the regions for a specific OEM heterogeneity value κ . The right figure shows the changes in the regions when the OEM heterogeneity is κ' ($> \kappa$). As can be observed, the saturation-region and the no-sale region shrinks whereas the niche-region becomes larger.

Furthermore, they allow the management to consider and account for architectural features and the state of OEM capabilities when outlining a licensing strategy.

3.4 Discussion & Conclusions: Implications for Component Providers

This article focuses on the licensing of new component technologies to industrial markets of competing manufacturing firms. We build upon the standard economic models of licensing (e.g., see Kamien and Tauman, 1984) utilizing a multidimensional representation of component technology that captures both what the component does (functionality) and how well it does it (underlying technology). Also, to enable greater generalizability, we consider a general competition mechanism instead of any one specific competition model. Lastly, we consider explicitly licensing structures where a fixed-fee is charged in addition to the volume-based royalty.

We derive the optimal introduction strategy given the different operational and marketing levers that the technology provider has at her disposal: (i) product features such as underlying technology performance and the functionality, and (ii) different licensing mechanisms. Our results provide important managerial insights along two dimensions summarized below.

3.4.1 Integrate or Not

Some technology providers have recently started shifting their technology focus towards offering greater functionality in their component technologies. For instance, Intel, citing their recent success with the Centrino technology (which combines the traditional microprocessor with wireless functionality), has announced a new “platformization” strategy suggesting a strategic shift towards augmenting superior performance with additional and richer functionality.

However, such strategic shifts towards greater functionality is not universal. In the hearing instruments industry, Knowles, the dominant core component technology provider with upward of 80% market-share, employs an approach diagonally opposite to Intel’s strategy. In an extended case-study, Lotz (1998), states that “[Knowles has] has maintained the same functionality in a component, and concentrated on making it smaller and smaller.” This focus on improving the underlying performance instead of enhancing the functionality highlights the stark difference between their “performance-focused” strategy and Intel’s “platformization” strategy. Though, numerous justifications may exist for this, our results allow us to identify some of the reasons for these differences in strategies.

Intel’s microprocessor and the associated end-product have significantly less complex product interfaces compared to the interfaces in the Knowles’ hearing instruments. Our results indicate that less complex product interfaces diminish the effect of integration decision (f) on the intergration risk ($p(f, K)$), and consequently lead to larger saturation regions. Thus, Intel, by the nature of the end-product that its components are employed in, may be less adversely affected by loss of market share despite its functionality decision.

However, one of the main insights derived from our analysis is the danger of “over-integration.” This may lead to loss of differentiation among the OEMs and consequently lower profits for the provider. Since Intel finds itself in the saturation strategy already, additional integration presents an important challenge in terms of allowing sufficient flexibility for Intel’s industrial customers to differentiate.

The results obtained from the current study also provide us with the basis for offering empirically testable propositions relating to the effects of integration.

P1: *Integration has a positive effect on the provider's profits if she is a niche player.*

P2: *Integration has a weaker effect on provider's profits if she is a saturation player compared to the case where she is a niche player.*

An empirical test of the propositions may be conducted by analyzing the effect of integration on profits using the market-share (which proxies whether or not the firm is a saturation or niche player) as a moderating variable.

3.4.2 Role of Royalties

Our results on the licensing mechanism suggest an interesting dual role for royalties. Past literature has treated the superiority of royalty primarily through the lens of moral hazard and risk sharing. Our framework offers an alternate explanation: the royalty structure is not only a value appropriation mechanism, but also serves as a value creation mechanism. It allows the technology provider to actively modify and moderate the competition intensity between her customer OEMs. The insight supports the dominance of royalties attested by Rostoker (1984).

Our results relating to the use of royalties are summarized in the following empirically testable propositions.

P3 *Royalty would be associated with Saturation Strategy.*

P4 *Royalty would be associated with greater competition intensity.*

In this article, we have developed a model of introduction and licensing of component technologies while explicitly accounting for competitive interactions between the potential licensees. We utilize an operational perspective of component technologies, which captures the essential multidimensional aspect of components, to offer managerial intuition into the licensing phenomenon. Still, as with any other mathematical model of real-world phenomenon, the results are subject to the limitations imposed by our modelling assumptions and caution must be exercised when translating our results into real-world contexts.

Models of licensing, to our knowledge, have disregarded the negotiation process that often accompanies technology licensing. Such considerations must be accounted for in future research both from a normative perspective to understand how licensing should be

conducted and from a descriptive perspective to understand the broader implications of negotiations in technology licensing. Furthermore, there is a lack of empirical verification of much the theoretical predictions of licensing literature. Thus, empirical verification of the relationships we proposed remains part of our future research agenda.

CHAPTER IV

TECHNOLOGY CODEVELOPMENT: CASE OF REVENUE/COST SHARING AGREEMENTS

Codevelopment is the mechanism by which two (or more) independent economic entities engage in a non-equity based, short-lived, collaborative project designed to exploit a specific market opportunity. In the recent years there has been a spate of such activities as confirmed by the National Science Foundation's whitepaper titled Science and Engineering Indicators (2004). Figure 13 also seem to indicate that the number of such codevelopment activities is on the rise over the past several years and underscore the importance of understanding how such collaborative projects may be managed.

A number of reasons such as time-to-market, access to complementary resources, and ability to share market/technical risk have been cited for the increase in number of non-equity based, short-lived, collaborative product development projects. In this chapter, we examine settings of codevelopment where two independent firms engage in a joint effort to exploit a specific market opportunity while facing both internal (development) and external (market) uncertainty. We construct a model that captures the main operational dimensions: individual effort levels and the timing and terms of the contract required to ensure resource commitment from the other party.

Our main result indicate that uncertainty, both in the product development process and the market estimates, play an important role in when and what contract is negotiated. In the presence of high uncertainty the firms may find it optimal to delay the contract signing till uncertainty is sufficiently resolved. However such delays may also lead to each firm expending lesser resources (holdup problem) as payoffs are not guaranteed. Optimally delayed contracts represent, to our knowledge, a new result that arises endogeneously through explicit consideration of the important product development variables of uncertainty.

The rest of the chapter is organized as follows. In §4.1 a summary of a case study of a

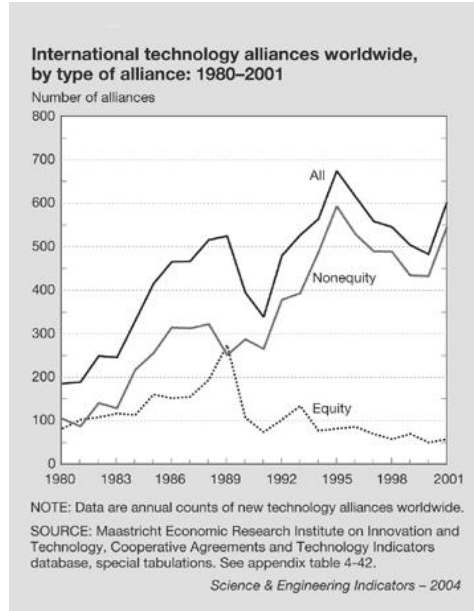


Figure 13: Industry Trends in Co-development

specific codevelopment project and some key observations about the same is offered. §4.2 reviews some key literature from economics and marketing that have examined the mechanism of contracting and reasons for potential delays in reaching agreements in collaborative situations. The main results are derived in §4.4. §4.5 concludes by offering the practical and theoretical implications of the main findings of the study.

4.1 Delta-3M Codevelopment: A Case Study

On September 3rd 1998, Swiss Air flight 111 with service from New York JFK to Geneva, plunged into the Atlantic Ocean off Nova Scotia shortly after takeoff. The Canadian Transportation Safety Board (TSB) conducted an extensive investigation into the causes for the crash and concluded that the culprit was a cabin-fire due to an electrical spark. The specific type of insulation material used (a form of polymer called metallized polyethyleneteraphthalate or MPET) allowed an electrical spark to quickly turn into a cabin-fire shorting out the electronic systems and causing malfunctioning of the aircraft control systems. TSB, subsequent to their investigation, recommended that such insulation be removed and imposed stringent safety standards on the insulation used in aircrafts (TSB recommendation

A99-07).

In the United States, FAA followed up with airworthiness directives (AD 2000-11-01 and AD 2000-11-02) applicable to certain classes of McDonnell Douglas aircrafts that mandated a determination of whether and at what locations the MPET insulation blankets are installed, and the replacement of all such insulation blankets. The initial directive required this to be carried out in 4 years, but subsequent industry pressure and the enormous costs that airlines would incur in following this directive convinced FAA to extend the compliance time to 5 years.

The solution that the aircraft manufacturer, Boeing, introduced was costly both in terms of actual price and in terms of maintenance time required. Delta TechOps, a division of Delta Airlines specializing in aircraft maintenance, decided to work with 3M to jointly develop and market an alternate solution. The alternate solution, named Nextel Flame Shield, was a type of ceramic paper that offered a durable, easy-to-install, lightweight barrier that would isolate the MPET from ignition sources. Since the installation time required for this alternate solution was considerably shorter, the aircrafts could return to service much sooner thus reducing the overall cost on the airlines.

The development, which required the two partners to interact and exchange information on a frequent basis, was started off with a simple memorandum of understanding without agreeing to any of the specific details of how costs would be split and/or revenues shared. Since time-to-market was considered to be an important concern, these contract details were to be negotiated later and was not allowed to hold up the product development. An attempt was made to keep track of each partner's contribution, but was quickly abandoned after the data grew unmanageable and it became clear that it was nearly impossible to reach consensus on who originally proposed a certain idea.

Despite the best efforts of both legal teams to reach an agreement on the exact details of cost/revenue sharing, negotiations went on till nearly the end of the product development. This observation - contracts may not always be signed before starting a codevelopment project and may be left out for future negotiation - is not isolated to the Delta-3M case study we conducted. Academic literature has long recognized the classic holdup problem

where firms would be unwilling to allocate resources without ensuring that they are able to appropriate rents. However, our observation seems to run counter to the conventional reasoning behind the holdup problem. This study examines a setting where a negotiation process runs parallel to the product development process, and it tries to resolve this apparent violation of holdup argument and to determine the reasons (if any) for signing contracts later in the NPD process. Furthermore, the study also examines the implications to profitability due to delayed contract.

4.2 Literature Review

There are two main streams of literature that are relevant to our research question. From the methodological perspective economists have examined negotiation processes and have obtained sharp results pertaining to delays in signing contracts. A seminal article by Rubenstein (1982) proposed an extensive form game involving alternating offers that had a unique subgame perfect equilibrium consistent with the cooperative nash bargaining solution. One key property of the Rubenstein equilibrium is that there are no delays in reaching an agreement on the division of payoffs. Since then a number of economists and game theorists have studied the causes for delays in bargaining and posited information asymmetry as one of the reasons. The main finding arising from such a modelling approach is the existence of multiple equilibria some of which exhibit delays (see for example Admati and Perry, 1987). However, the explanation of asymmetric information has been generally viewed as unsatisfactory by most economists, possibly because such multiple equilibria offer little guidance to prediction (Gul et al., 1986; Gul and Sonnenschein, 1988). For a more complete review of the bargaining literature and the mixed findings see Binmore (1987), Roth (1985).

The main finding from the game theoretic bargaining literature can be summarized as follows: With no information asymmetry, contracts are always signed beforehand, and even with information asymmetry, delays are not necessarily present for all the equilibria. Our case study illustrates that when the joint effort is between two parties who have collaborated before (which might proxy lack of significant information asymmetry relating to firm capabilities), there may still be significant delays in signing contracts. Thus, we focus on

the product development settings exemplified by the case study, and we analyze situations of codevelopment while accounting for key product development variables such as internal (development) and external (market) uncertainty. We find that delays may in fact be optimal, and thus that the product development process has some unique effects on the bargaining process that have so far not been captured in economic models of bargaining.

The topic of joint product development (and in specific joint ventures) have received much attention from the strategy literature (Gulati, 1998). The focus within this stream has been to find variables, such as trust (Mohr and Spekman, 1994) and complementary goals (Gates, 1993), complementary resources (Dyer and Singh, 1998), that explain joint development success. Our focus, in contrast, is more process-based and involves examining the joint product development process to both explain rationales for delayed contracts and for offering managerial recommendations for when negotiation should be completed and when it should be aggressively pursued.

4.3 Model setup

Consider two firms A and B who decide to jointly develop a new product. We assume that a loose Memorandum of Understanding (MOU) is signed allowing the firms to work together without requiring any firm commitment of resources and/or commitment to how potential profits may be shared.

Following a process-based view of product development, we assume that the product development is a stage-gate process with milestones after each significant development step. For ease of exposition, we consider a two period model and assume that resources may be deployed in the two periods towards the joint development effort. The model setup is split into three parts: (i) characteristics of the development efforts, and how individual efforts map onto the final joint value of the development project, (ii) features of information acquisition associated with the temporal process nature of the joint product development, and (iii) the negotiation process and the type of contracts that may be agreed on.

4.3.1 Individual Development efforts and Value of Project

Let the resource committed towards the joint product development during stage i ($i = 1, 2$) by firm A be r_{iA} . The performance enhancement in firms A 's contribution resulting the resource commitment of r_{iA} is random and equal to $\mathbf{P}(\mathbf{r}_{iA})$.

The total revenue that may be obtained from the joint development is given by

$$\Pi = \mathbf{M}V(\mathbf{P}(\mathbf{r}_{1A}) + \mathbf{P}(\mathbf{r}_{2A}), \mathbf{P}(\mathbf{r}_{1B}) + \mathbf{P}(\mathbf{r}_{2B}))$$

where \mathbf{M} is a random variable representing the (uncertain) market potential, and $V(P_A, P_B)$ represents the revenue that can be realized from a single customer when the firm A 's total contribution is P_A and B 's total contribution is P_B .

4.3.2 Information Acquisition and the Development Process

For concreteness assume that the development uncertainty may be represented as follows: $\mathbf{P}(\mathbf{r}) = r + \eta$ where η is drawn from a normal distribution with mean 0¹. Furthermore, suppose that the market potential \mathbf{M} is given by $m + \epsilon_1 + \epsilon_2$. Thus, the market potential \mathbf{M} consists of two parts: a deterministic part m , and an uncertain part $\epsilon_1 + \epsilon_2$ where ϵ_1 and ϵ_2 are normal random variables with mean 0.

An important aspect of the process-based view of product development is its temporal nature. Thus, we assume that uncertainty gets (gradually) resolved over time as information is accumulated. Hence, the development uncertainty represented through η_{iA} is revealed at the end of period i and can be observed by both parties. Similarly, although at the beginning of period 1 both ϵ_1 and ϵ_2 are uncertain, the firms are able to partially resolve the market uncertainty at the end of period 1 through information collection. Thus, ϵ_1 may be observed at the end of period 1 by both parties.

We have purposely disregarded accounting for any information assymetries about the capabilities (and/or cost structures) for two reasons: (i) in contexts such as the codevelopment effort by Delta and 3M, the long relationship the firms have had prior to the codevelopment

¹The requirement of normal distribution is purely for the purposes of exposition. The results can be shown to hold for a much larger set of two parameter distributions characterized by location and scale invariance (i.e., distributions which can be normalized to have mean 0 and variance 1). For a more technical treatment of location and scale invariant distributions see Meyer (1987).

project makes it less likely that there would be information asymmetries between the partners, and (ii) economics literature has demonstrated that information asymmetries result in signalling behavior that may lead to delayed contracts. Our focus is on understanding the effects of NPD variables on the contract negotiation process, and thus we have chosen to disregard the well-understood effect of information asymmetries.

4.3.3 Negotiation Process and the Contract

The contract that splits the total proceeds and allocates the efforts (development tasks) may be signed at any stage of the development process. Thus, the contract may be signed (i) before any resources are deployed (i.e., before period 1), or (ii) when the project is going on (i.e., after period 1) or (iii) after the project is completed (i.e., after period 2). We assume that if no agreement can be reached even at the end of the project, then no value is created for any of the parties (i.e., outside option has economic value 0).

We assume that when a contract is signed, it should specify (i) the efforts in each of the remaining periods for each party (i.e., r_{iA} and r_{iB}), and (ii) the division of final revenues (Π_A and Π_B).

Following Rubenstein (1982), we consider a negotiation process where at each stage one party can make an offer which the other party may accept or reject. If the offer is accepted, then the efforts are expended based on the contract terms, otherwise if the offer is rejected, the firms may individually choose whatever effort levels they want (including not putting any effort), and the game moves onto the next stage.

The probability of firm A making an offer at any stage is p . Note that p may be interpreted as the negotiation power of firm A , and that $p = \frac{1}{2}$ implies equal negotiation power. This specification has been used in past literature to force symmetry between the players Binmore (1987). The current analysis examines the case of equal negotiation power ($p = 0.5$) representing codevelopment partners of equal size. In a research study currently underway, we attempt to evaluate the effect of asymmetric power (for instance the codevelopment project between a large Pharma and a small Biotech firm) on optimal contracting.

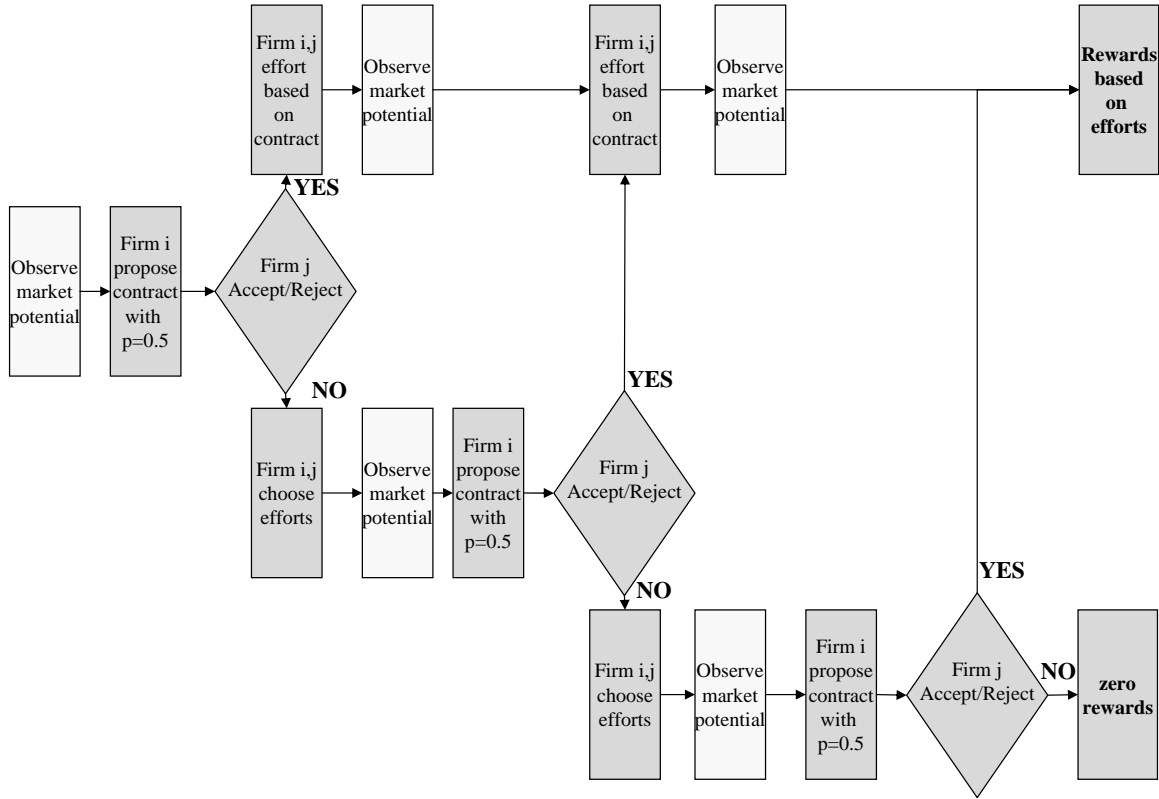


Figure 14: Sequence of decisions for the Codevelopment Process

Figure 14 shows the timing and sequence of decisions in the negotiation and product development game. Before the project has commenced both parties may observe the deterministic part of the market potential m . One of the firms propose a contract which the other party accepts or rejects. In case of acceptance of contract terms, the contract is signed and effort is expended as mandated by the contract. Otherwise, each firm may individually (and independently) decide how much effort to dedicate².

After the first period, the firms may again observe the outcome from their efforts (i.e., $P(r_{1A})$ and $P(r_{2A})$). Furthermore, a part of the market uncertainty ϵ_1 is also resolved and may be observed by the two parties. One of the firms again proposes a contract that the other firm may accept or reject. In case of acceptance, effort mandated by the contract is expended, otherwise the game continues with each firm independently deciding the effort to expend in the second period.

²Note that the firms may even decide to devote no effort in case no contract has been signed so far.

4.4 *Optimal Length of Negotiation Period*

One of the fundamental reasons often advocated towards joint product development is possible complementary capabilities. We employ the functional form $V(\cdot, \cdot)$ to model the possible synergies that may exist between the two firms product development capabilities.

If the firm's efforts are complementary, the revenue function $V(\cdot, \cdot)$ will be supermodular. For instance, if the resources are aimed towards developing complementary sub-components (such as software and the hardware to run it on), it is likely the case that $V(P_A, P_B)$ will be supermodular in (P_A, P_B) .

On the other hand, if the resources are being committed towards efforts that are substitutes it is likely the case that $V(\cdot, \cdot)$ is submodular. As an example consider two firms simultaneously searching for a solution with the understanding that the better of the two solutions will be employed. This function, $\max\{P_A, P_B\}$, is submodular.

We analyze these two settings below.

4.4.1 *Case of Complementary Efforts/Capabilities*

In Theorem 4 and 5 we characterize the length of negotiation period and when the contract would be signed.

Theorem 4 *A mutually acceptable contract will be offered by the (random) proposer at the beginning of period 2 if no contract has been signed earlier.*

Theorem 4 states that the negotiations are never delayed till the end of the project. Intuitively, the rationale for delaying the negotiations is so as to resolve market and/or development uncertainty **and** to take actions contingent on the newly revealed situation. However, delaying it beyond period 2 yields no benefits as all the actions have already been taken by period 2. Hence, contracts are never delayed beyond the end of the project.

Theorem 5 *A mutually acceptable contract will be offered by the (random) proposer at the beginning of period 1 if (i) $\sigma(\eta_{1.}) \leq \sigma_1^*$, or (ii) $\sigma(\epsilon_1) \leq \sigma_2^*$*

Theorem 5 states that there is a threshold uncertainty below which the partners would not wish to delay contracting. However, when either the market uncertainty or the development uncertainty is beyond a threshold, contracting can be delayed till beginning of 2nd period at which time the uncertainty would be at least partially resolved³.

Propositions 16 and 17 offer results that allow interesting comparisons to past results from real options and economics literature.

Proposition 16 *The value of the joint development effort is increasing in the market uncertainty $\sigma(\epsilon_1)$.*

Proposition 17 *The resources committed by the partners are higher when operating under a contract than without.*

The first result is similar to the real options literature which suggests that value of a project increases with market uncertainty. This occurs because with higher uncertainty, the upside becomes higher and can be exploited by suitable decisions. The second result is identical to the classic holdup/free-rider problem studied in economics.

Uncertainty, as often seen in real options literature, has the ability to enhance the value of delayed decisions. Furthermore, uncertainty also has an impact on holdup problem possibly aggravating it. In the case of supermodular functions our results indicate that the first effect (value enhancement due to real options result) dominates. This comes about because the holdup problem is not very dominant in the supermodular settings as the efforts are actually complements. However, our numerical examples suggest that, for a subset of submodular functions, the holdup problem may become dominant decreasing the value of a project as uncertainty increases.

4.4.2 Case of Substitute Capabilities

Due to mathematical intractability of submodular games, we adopt a specific functional form $V(P_A, P_B) = (P_A + P_B)$ to capture the case of substitute capabilities. Note that the

³The results can be easily extended to n periods, and a sample path of market potential and effort realizations can always be found that leads to contracts delayed by an arbitrary time.

function is both submodular and supermodular and the results from previous subsection still apply. However, for this special case, we may obtain sharper results as to when the contract is signed.

Proposition 18 *Let the coefficient of variation of the market potential be $\psi = \frac{\sigma(\epsilon_1)}{m}$. Then, there is a threshold ν such that the contract is signed before the project iff $\psi \leq \nu$*

Thus, it can be seen that even for this specific case of submodular function, the results retain their basic structure. Furthermore, the coefficient of variation plays an important role in deciding when the contract is signed. The contract is always signed upfront before the project has commenced when the uncertainty is low (i.e., low $\sigma(\epsilon_1)$) or when the expected market potential is high (i.e., high m).

4.5 Conclusions

Motivated by a case study we conducted involving joint development of a new component for aircrafts by two firms, Delta Airlines and 3M, we explore the negotiation and contracting process in an NPD codevelopment setting. Based on our observations from the case study, we have modelled and analyzed a generic setting of codevelopment. We employ a process-based approach to modelling the codevelopment question and focus on the information acquisition and uncertainty resolution characteristic of processes. Our analysis indicates that product development variables such as market and development uncertainty have important implications to when and what contract should be negotiated and agreed to.

Our results indicate that under conditions of high market or development uncertainty firms may optimally delay signing a contract till at least a part of the uncertainty is resolved. Furthermore, our analysis shows that delayed contracts mimic some of the behavior of real options and that the value of delaying signing a contract may be traced to added flexibility that firms retain without contract on their future actions. However, our analysis also indicates the competitive setting of codevelopment also leads to lower effort levels due to lack of commitment from other party. Hence, it is the balance of the two forces - loss in

value due to holdup resulting from lack of contract and value enhancement due to flexibility arising from the absence of contract - that determines when a contract is signed.

Additional research is required to ascertain the impact of negotiation power and to understand the effect of complimentary/substitute capabilities on the negotiation process as well as the value of the joint development projects.

APPENDIX A

SUPPLEMENT TO CHAPTER II

Appendix A is organized as follows. First, examples 1 and 2, and figures 15 and 16 referenced from the main text are given. Next, the summary and intuition behind the proofs of main results together with the formal proofs for these results are provided. Finally, a proof of observation 1 is provided.

Example 1

Table 4: Payoff matrix for the row player

	<i>ADOPT,ADOPT</i>	<i>ADOPT,NOT-ADOPT</i>	<i>NOT-ADOPT,ADOPT</i>	<i>NOT-ADOPT,NOT-ADOPT</i>
<i>ADOPT</i>	$\frac{2}{2+2+2} - 0.14 = 0.19$	$\frac{2}{2+2+1} - 0.14 = 0.26$	$\frac{2}{2+1+2} - 0.14 = 0.26$	$\frac{2}{2+1+1} - 0.14 = 0.36$
<i>NOT-ADOPT</i>	$\frac{1}{1+2+2} = 0.20$	$\frac{1}{1+2+1} = 0.25$	$\frac{1}{1+1+2} = 0.25$	$\frac{1}{1+1+1} = 0.33$

The following example illustrates the basic mechanism for technology adoption in a single-period context. Consider 3 OEMs currently employing technology $\tau_0 = 1$ and let total end-product market size = 1. Hence, each of them currently have payoff $\frac{1}{1+1+1} = \frac{1}{3}$. Now suppose that the technology provider introduces a new technology $\tau = 2$ and prices it at 0.14. Let *A* represent the adopt strategy, and *N* the not-adopt strategy. Examination of the payoff matrix in Table 4 reveals that, if the OEMs simultaneously decide on adoption, then there would be three Nash equilibria $\{(A, A, N), (A, N, A), (N, A, A)\}$. Similarly if the OEMs sequentially decide (i.e. OEM 1 decides before OEM 2 and OEM 2 decides before OEM 3), then (A, A, N) is the unique subgame perfect Nash equilibrium. Notice that in our example, the OEMs end up worse off than if none of them had adopted¹, but because of the prisoners' dilemma structure of the game, OEMs are compelled to adopt (similar to the "confess" strategy in the prisoners' dilemma game).

¹The result is not an artifact of the constant-sum game we consider. It holds for a large class of models of competition including differentiated Bertrand and Cournot competition. For a formal treatment see Erat and Kavadias (2005)

Example 2

Consider 3 OEMs, all of whom initially use technology 1. The technology provider introduces technology $T = 2$, at the same time decides to develop technology $\alpha T = 2.1$. Let $\delta = 1$ and $m = 1$. At the subgame perfect equilibrium the provider charges prices $W_1 = 0.28$ and $W_2 = 0.14$. These prices induce an equilibrium where 2 OEMs adopt technology T in the first period, and in the second period the OEM who has not adopted T earlier adopts technology αT .

In this same example if the technology provider decided to develop technology $\alpha T = 4$, at subgame perfect equilibrium, the provider charges prices $W_1 = 0.13$ and $W_2 = 0.13$. Further, these prices induce an equilibrium where all the OEMs adopt T and αT in periods 1 and 2 respectively.

Figures for Heterogeneous OEM markets

The left column of Figures 15 and 16 illustrate the case when the difference in capabilities between H OEMs and L OEMs is small, and the right column for the case where the difference in capabilities is relatively large.

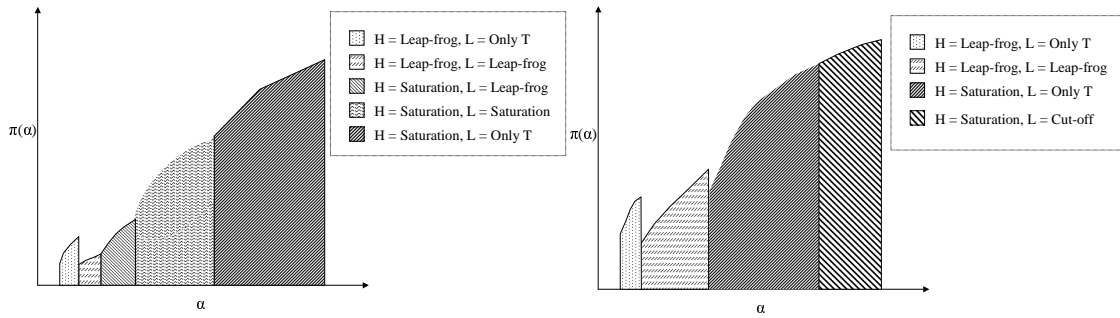


Figure 15: Two examples of Provider's revenues corresponding to heterogeneity in Technology Enhancing Capabilities

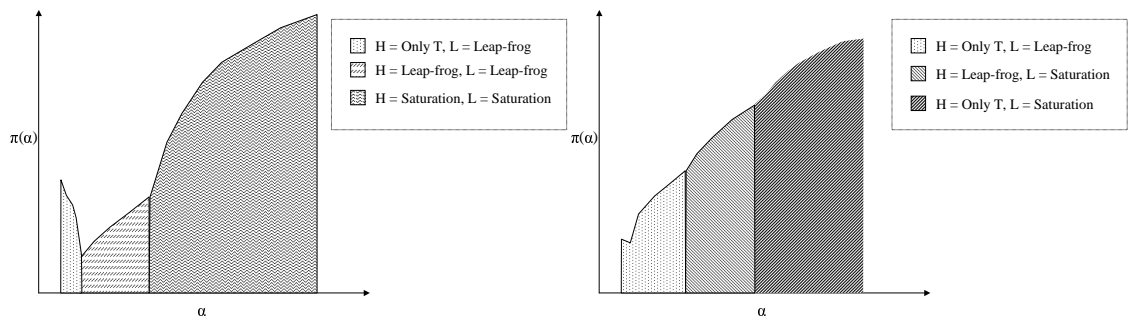


Figure 16: Two examples of Provider's revenues corresponding to heterogeneity in Technology Independent Capabilities

For ease of exposition, we call the first-period adopters T-OEMs, and the first-period non-adopters 1-OEMs (i.e. T-OEMs adopt and utilize technology T in the first period, and 1-OEMs do not adopt T and utilize technology 1 in the first period).

Proof of theorem 1

We prove the theorem using backward induction. The 5 stages are illustrated in Figure 1 of the main text. In the first period (2^{nd} stage), the technology provider, given the second period technology development decision αT , sets the price for technology T at W_1 . Then, (at the 3^{rd} stage) each OEM makes an adopt/not-adopt decision² about technology T . In the second period (4^{th} stage), the provider prices the second-period technology (αT) at W_2 . Finally (at the 5^{th} stage) each OEM decides whether to adopt/not-adopt αT .

The **history** (or the sequence of decisions in the past) for this 5-stage game is as follows. The history at the third stage is the price $\{W_1\}$ set by the firm in the first period. The history at the fourth stage is the tuple $\{W_1, f\}$ where f is the fraction that adopted in the first period. The history at the fifth and final stage is the tuple $\{W_1, f, W_2\}$.

Notice that we have collapsed some of the history, in particular only the total number of adopters and not the specific adopters are kept in history. Given that all the firms are identical, the only information the technology provider needs so as to set the price is the total number of adopters in the first period.

Summary of proof

Lemma 1 shows that irrespective of the prices charged for the second-period technology, the second-period outcome is such that the T-OEMs adopt again in the second period only if all the 1-OEMs adopt in the second period. Intuitively, the increase in revenues an OEM accrues by adopting a new technology depends on the technology increment, and hence switching from 1 to αT (for 1-OEMs) leads to larger increase in revenue compared to upgrading from T to αT (for T-OEMs).

According to Lemma 2, at the final stage of the game, the number of adopters cannot grow beyond the point where the revenue gain to an additional adopting OEM is equal to

²Note that this adopt/not-adopt decision depends not only on current (1^{st} period) payoffs, but also on (discounted) future 2^{nd} period revenues.

the price paid for the technology (i.e. marginal revenue for the marginal OEM \leq price paid for the technology).

Lemma 3 demonstrates an important result: in the second period, the technology provider sells the technology αT either (a) to all the 1-OEMs, or (b) to all the OEMs irrespective of their technology.

Lemma 5 gives the adoption behavior of the OEMs (i.e # of OEMs who adopt) in the first period for an arbitrary price W_1 . Lemma 5 can also be equivalently viewed as determining the price W_1 that induces an arbitrary adoption pattern.

Finally, we demonstrate that if the technology provider induces partial adoption in the first period, then it must necessarily be true that she sells only to the 1-OEMs in the second period. The only alternative is that the the technology provider induces full adoption in both the periods. These two strategies are termed the leap-frogging strategy and saturation strategy respectively. Finally, we conclude the proof by noting that the maximum of the two revenues, leap-frogging revenue and saturation revenue, determines the actual introduction strategy followed by the profit maximizing technology provider.

An extended list of notations used in Appendix A is presented below. Also, as a note on the presentation style, to maintain a linear presentation of the proofs, we present the proofs of any auxillary lemmas required to prove the main results along with the main proofs.

f	:	fraction of adopters in 1 st period
$\theta_f = nfT + n(1-f)$:	“Total” technology (performance) in period 1
$\gamma_f T = (nf + n(1-f)\alpha)T$:	“Total” technology (performance) in period 2 assuming no 1-OEM remains
$W_1^p(f, \alpha) = \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} \right) + \delta m \cdot \frac{(T-1)(\gamma_f - 1)}{(T\gamma_f - T + 1)\gamma_f}$:	1 st period price to induce fraction f to adopt T
$W_2^p(f, \alpha) = m \cdot \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$:	2 nd period price to induce remaining $(1-f)n$ OEMs to adopt αT
$W_1^a = \frac{1}{n} - \frac{1}{nT - T + 1}$:	1 st period price that induces all the OEMs to adopt T
$W_2^a(\alpha) = m \cdot \left(\frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \right)$:	2 nd period price that induces all the OEMs to adopt αT
$\Phi(f) = \frac{(1-f)(\alpha T - 1)(\gamma_f - \alpha)}{(\gamma_f T - \alpha T + 1)\gamma_f} - \frac{(\alpha - 1)(n - 1)}{(n\alpha - \alpha + 1)n}$		
$\Psi(f) = \frac{\delta m \frac{(T-1)(\gamma_f - 1)}{(T\gamma_f - T + 1)\gamma_f} + \frac{T(T-1)}{\theta_f(\theta_f + T - 1)}}{\frac{(T-1)}{\theta_f(\theta_f - T + 1)} - \delta m \frac{(T-1)(\gamma_f - \alpha)}{(T\gamma_f - T\alpha + 1)(\gamma_f - \alpha + 1)}}$		
$F = \{f : \Phi(f) \geq 0, \Psi(f) \geq 0\}$:	Feasible values of f that the technology provider can induce
$f^*(\alpha) = \arg \max_{f \in F} \left\{ \begin{array}{l} fW_1^p(f, \alpha) \\ +(1-f)W_2^p(f, \alpha) \end{array} \right\}$:	Fraction of 1 st period adopters under leap-frogging
$\pi_p(\alpha) = n \left[\begin{array}{l} f^*(\alpha)W_1^p(f^*(\alpha), \alpha) \\ +(1-f^*(\alpha))W_2^p(f^*(\alpha), \alpha) \end{array} \right]$:	Provider’s revenues under leap-frogging
$\pi_a(\alpha) = n(W_1^a + W_2^a(\alpha))$:	Technology provider’s revenue under saturation

Formal proof of theorem 1

Lemma 1 *Given any history $\{W_1, f, W_2\}$ at the fifth stage, if p is the number of T-OEMs who adopted again in the second period, and q is the number of 1-OEMs who adopted in the second period, then $\{p > 0\} \implies \{q = (1 - f)n\}$.*

Proof. We prove the lemma by contradiction. Suppose, corresponding to the price W_2 , the equilibrium induced has p T-OEMs, and q 1-OEMs adopting the technology αT . Further, let $\{p > 0\}$ and $\{q \neq (1 - f)n\}$. Define the following

$$\beta_{p,q} = (fn - p)T + p\alpha T + (1 - f)n - q + q\alpha T$$

Since, the induced adoption pattern is an equilibrium, none of the OEMs have any incentive to deviate. In specific, if π_A^T is the payoff a T-OEM makes by deciding to adopt, and if π_N^T is his payoffs by switching to a non-adopt decision, then $\pi_A^T \geq \pi_N^T$. That is

$$\begin{aligned} m \frac{\alpha T}{\beta_{p,q}} - W_2 &\geq m \frac{T}{\beta_{p,q} - \alpha T + T} \\ W_2 &\leq m \frac{\alpha T}{\beta_{p,q}} - m \frac{T}{\beta_{p,q} - \alpha T + T} \end{aligned}$$

Similarly, for a 1-OEM who didnt adopt (note that there is always one such 1-OEM since $q \neq (1 - f)n$), $\pi_N^1 > \pi_A^1$ where π_N^1 and π_A^1 are the payoffs of a 1-OEM before and after deviation respectively. That is

$$\begin{aligned} m \frac{1}{\beta_{p,q}} &> m \frac{\alpha T}{\beta_{p,q} - 1 + \alpha T} - W_2 \\ W_2 &> m \frac{\alpha T}{\beta_{p,q} - 1 + \alpha T} - m \frac{1}{\beta_{p,q}} \end{aligned}$$

Hence, it is necessary that

$$m \frac{\alpha T}{\beta_{p,q} - 1 + \alpha T} - m \frac{1}{\beta_{p,q}} < m \frac{\alpha T}{\beta_{p,q}} - m \frac{T}{\beta_{p,q} - \alpha T + T}$$

Simple algebra verifies that this inequality is never satisfied (the increase in revenues when upgrading from technology 1 to αT is greater than the increase in revenues when upgrading from technology T to αT). This contradiction proves the claim (i.e. $\{p > 0\} \implies \{q = (1 - f)n\}$). ■

Lemma 2 Given any history $\{W_1, f, W_2\}$ at the fifth stage the number of adopters in the second period is given by $n\omega$ where ω is the largest value satisfying

$$W_2 \leq m \left(\frac{\alpha T}{\beta_\omega} - \frac{1_{\{\omega \leq 1-f\}}1 + 1_{\{\omega > 1-f\}}T}{\beta_\omega - \alpha T + 1_{\{\omega \leq 1-f\}}1 + 1_{\{\omega > 1-f\}}T} \right)$$

where $\beta_\omega = 1_{\{\omega \leq 1-f\}}(1-f-\omega)n + [1_{\{\omega \leq 1-f\}}f + 1_{\{\omega > 1-f\}}(1-\omega)]nT + \omega n \alpha T$

Proof. If $n\omega$ OEMs adopt in the second period, then by Lemma 1, the OEM market has the following structure with respect to the employed technology

$$\begin{aligned} n\omega & : \# \text{ of } \alpha T \text{ users} \\ n [1_{\{\omega < 1-f\}}f + 1_{\{\omega \geq 1-f\}}(1-\omega)] & : \# \text{ of } T \text{ users} \\ n 1_{\{\omega < 1-f\}}(1-f-\omega) & : \# \text{ of } 1 \text{ users} \end{aligned}$$

Let

$$\begin{aligned} G_1(\omega) & = m \frac{\alpha T}{\beta_\omega} \\ G_2(\omega) & = m \frac{1_{\{\omega \leq 1-f\}}1 + 1_{\{\omega > 1-f\}}T}{\beta_\omega - \alpha T + 1_{\{\omega \leq 1-f\}}1 + 1_{\{\omega > 1-f\}}T} \\ G(\omega) & = G_1(\omega) - G_2(\omega) \end{aligned}$$

where $G_1(\omega)$ is the payoff of a second-period adopter, and $G_2(\omega)$ is the payoff of a T-OEM or 1-OEM (depending ω) who switches to a not-adopt decision in the second period. For $n\omega$ to be an equilibrium, it is necessary and sufficient that none of the OEMs have incentives to deviate. Consider the following two cases.

Case 1: $\omega < 1-f$

All the 1-OEMs who adopt in the second period would stick to their adoption decision iff $G_1(\omega) - W_2 \geq G_2(\omega)$, that is $G(\omega) \geq W_2$. Furthermore, the 1-OEMs who decide not to adopt in the second period stick to their decision iff $G_1(\omega + \frac{1}{n}) - W_2 < G_1(\omega + \frac{1}{n})$, that is $G(\omega + \frac{1}{n}) < W_2$ (since if a 1-OEM switches to adopt decision, the total fraction of adopters increase by $\frac{1}{n}$).

Further, from lemma 1, if $G(\omega + \frac{1}{n}) < W_2$ for any $\omega < 1-f$ (i.e. at least one of the 1-OEMs havent adopted), all the T-OEMs stick to their not-adopt decision.

Hence, for $\omega < 1 - f$, $n\omega$ is the number of adopters in second period iff $G(\omega) \geq W_2$, and $G(\omega + \frac{1}{n}) < W_2$.

Case 2: $\omega \geq 1 - f$

The argument is similar to case 1. All the T-OEMs who adopt in the second period stick to their adopt decision iff $G(\omega) \geq W_2$, and all the T-OEM who decide not to adopt in second period stick to their decision iff $G(\omega + \frac{1}{n}) < W_2$. Similarly, all the 1-OEMs adopt in second period (by Lemma 1) and will stick to their decision (since $W_2 \leq G(\omega)$).

Thus, for $\omega \geq 1 - f$, $n\omega$ is an equilibria iff $G(\omega) \geq W_2$, and $G(\omega + \frac{1}{n}) < W_2$.

Combining the two cases, we get, for $n\omega$ to be an equilibria, it is necessary and sufficient that $G(\omega) \geq W_2 > G(\omega + \frac{1}{n})$.

Finally, to show that this equilibrium $n\omega$ is unique, we prove that $G(\omega)$ decreases in ω . Suppose $\omega < 1 - f$.

$$\begin{aligned} G(\omega) &= m \left(\frac{\alpha T}{\beta_\omega} - \frac{1}{\beta_\omega - \alpha T + 1} \right) \\ G(\omega + \frac{1}{n}) &= m \left(\frac{\alpha T}{\beta_\omega - 1 + \alpha T} - \frac{1}{\beta_\omega} \right) \\ G(\omega + \frac{1}{n}) - G(\omega) &= m \left(\frac{\alpha T}{\beta_\omega - 1 + \alpha T} - \frac{1}{\beta_\omega} \right) - m \left(\frac{\alpha T}{\beta_\omega} - \frac{1}{\beta_\omega - \alpha T + 1} \right) \\ &= -m \frac{(\beta_\omega - \alpha T - 1)(\alpha T - 1)^2}{(\beta_\omega - \alpha T + 1)(\beta_\omega + \alpha T - 1)\beta_\omega} < 0 \end{aligned}$$

Similarly, algebra confirms that $G(\omega + \frac{1}{n}) < G(\omega)$ for $\omega \geq 1 - f$ and $G(\omega = 1 - f) < G(\omega = 1 - f - \frac{1}{n})$ (upon request detailed calculations are available from the authors).

That is, $G(\omega)$ is a decreasing function of ω . Hence, we can state the condition $G(\omega) \geq W_2 > G(\omega + \frac{1}{n})$ as follows - the equilibrium ω is the largest ω value that satisfies the inequality $W_2 \leq G(\omega)$. ■

In the subsequent lemmas we suppress the subscripts of θ_f and γ_f , and instead use θ and γ , whenever possible in order to simplify the notation.

Lemma 3 *Given any first-period history $\{W_1, f\}$ the technology provider's best response function is given by*

$$W_2(f) = \begin{cases} m \frac{(\alpha-1)(n-1)}{(n\alpha-\alpha+1)n} & \text{if } \frac{(1-f)(\alpha T-1)(\gamma-\alpha)}{(\gamma T-\alpha T+1)\gamma} < \frac{(\alpha-1)(n-1)}{(n\alpha-\alpha+1)n} \\ m \frac{(\alpha T-1)(\gamma-\alpha)}{(\gamma T-\alpha T+1)\gamma} & \text{otherwise} \end{cases}$$

The corresponding number of second-period adopters are n and $(1 - f)n$ respectively.

Proof. Lemma 2 can also be looked on as determining the price W_2 which induces $n\omega$ OEMs to adopt. That is, by setting W_2 s.t. $G(\omega) \geq W_2 > G(\omega + \frac{1}{n})$, the technology provider induces $n\omega$ OEMs to adopt ($G(\omega)$ is as defined in Lemma 2). Since the provider maximizes profits, she charges $G(\omega)$, the highest possible value that still induces $n\omega$ OEMs to adopt. Her second-period revenues corresponding to $n\omega$ OEMs adopting is

$$\pi_2(\omega) = n\omega G(\omega)$$

ω chosen by the technology provider (indirectly by pricing at $G(\omega)$) is such that her second-period profits are maximized. We examine the structure of $\pi_2(\omega)$ by considering two separate cases.

Case i) $\omega < 1 - f$.

$$\begin{aligned} \pi_2(\omega) &= n\omega m \left(\frac{\alpha T}{\beta_\omega} - \frac{1}{\beta_\omega - \alpha T + 1} \right) \\ \pi_2\left(\omega + \frac{1}{n}\right) &= n\left(\omega + \frac{1}{n}\right)m \left(\frac{\alpha T}{\beta_\omega - 1 + \alpha T} - \frac{1}{\beta_\omega} \right) \\ \Delta\pi_2 &= \pi_2\left(\omega + \frac{1}{n}\right) - \pi_2(\omega) \\ &= n\left(\omega + \frac{1}{n}\right)m \left(\frac{\alpha T}{\beta_\omega - 1 + \alpha T} - \frac{1}{\beta_\omega} \right) - n\omega m \left(\frac{\alpha T}{\beta_\omega} - \frac{1}{\beta_\omega - \alpha T + 1} \right) \\ &= (\alpha T - 1)m \frac{(\beta_\omega - T\alpha)(\omega n - T\omega n\alpha + \beta_\omega) + (n\omega + 1)(\alpha T - 1)}{(\beta_\omega - \alpha T + 1)(\beta_\omega - 1 + \alpha T)\beta_\omega} > 0 \end{aligned}$$

Case ii) $\omega > 1 - f$.

$\pi_2(\omega)$ is increasing in ω (detailed algebra available from the authors).

That is $\pi_2(\omega)$ is increasing in the interval $[0, 1 - f)$ and the interval $(1 - f, 1]$. Hence, if the fraction ω that the provider induces to adopt is not equal to $1 - f$ or 1, it cannot be the provider's best response strategy. The profits corresponding to $\omega = 1 - f$ and $\omega = 1$ are respectively

$$\pi_2(1 - f) = n(1 - f)G(1 - f) = m \frac{n(1 - f)(\alpha T - 1)(\gamma - \alpha)}{(\gamma T - \alpha T + 1)\gamma}$$

and

$$\pi_2(1) = nG(1) = m \frac{(\alpha - 1)(n - 1)}{(n\alpha - \alpha + 1)}$$

Hence, the technology provider would chooses to price αT at $G(1-f)$ if $\pi_2(1-f) > \pi_2(1)$, otherwise prices at $G(1)$. ■

Lemma 4 *At the third stage for a history $\{W_1, f\}$ if the provider optimally induces $\omega = (1-f)$ to adopt technology αT , then for any history (W_1', q) such that $q < f$ the provider optimally induces $\omega = (1-q)$ to adopt αT .*

Proof. Similar to Lemma 3 it can be shown that $\frac{(1-f)(\alpha T-1)(\gamma_f-\alpha)}{(\gamma_f T-\alpha T+1)\gamma_f}$ is a decreasing function of f . That is

$$\left(\frac{(1-f)(\alpha T-1)(\gamma_f-\alpha)}{(\gamma_f T-\alpha T+1)\gamma_f} > \frac{(\alpha-1)(n-1)}{(n\alpha-\alpha+1)n} \text{ and } q < f \right) \Rightarrow \frac{(1-q)(\alpha T-1)(\gamma_q-\alpha)}{(\gamma_q T-\alpha T+1)\gamma_q} > \frac{(\alpha-1)(n-1)}{(n\alpha-\alpha+1)n}$$

Intuitively, the technology provider's strategy to sell to only the 1-OEMs in the second period becomes more profitable when the number of 1-OEMs increases. ■

Lemma 5 *Given a history $\{W_1\}$ the number of adopters in the first period is given by nf where f satisfies either*

$$(R1) \begin{cases} \Delta > -\frac{T(T-1)}{\theta_f(\theta_f+T-1)} + \frac{(T-1)}{\theta_f(\theta_f-T+1)} + \delta m \frac{(T-1)(\gamma_f-\alpha)}{(T\gamma_f-T\alpha+1)(\gamma_f-\alpha+1)} \\ \Delta \leq \delta m \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} \\ \frac{(1-f)(\alpha T-1)(\gamma_f-\alpha)}{(\gamma_f T-\alpha T+1)\gamma_f} \geq \frac{(\alpha-1)(n-1)}{(n\alpha-\alpha+1)n} \end{cases}$$

or (R2) $\begin{cases} \Delta > -\frac{(\theta_f^2-T^2+1)(T-1)}{(\theta_f-T+1)(\theta_f+T-1)\theta_f} \\ \Delta \leq 0 \\ \frac{(1-f)(\alpha T-1)(\gamma_f-\alpha)}{(\gamma_f T-\alpha T+1)\gamma_f} < \frac{(\alpha-1)(n-1)}{(n\alpha-\alpha+1)n} \end{cases}$

where $\Delta = W_1 - \left(\frac{T}{\theta_f} - \frac{1}{\theta_f-T+1} \right)$.

Proof. Suppose nf is the number of 1st period adopters (T-OEMs) at the equilibrium corresponding to the price W_1 . Define

$$\begin{aligned} \Delta &= W_1 - \left(\frac{T}{\theta} - \frac{1}{\theta-T+1} \right) \\ \text{i.e. } W_1 &= \Delta + \left(\frac{T}{\theta} - \frac{1}{\theta-T+1} \right) \end{aligned}$$

Notice that $\left(\frac{T}{\theta} - \frac{1}{\theta - T + 1}\right)$ is the price required to induce fraction f to adopt in a single-period version of our setting. Hence, Δ as defined above is a premium representing the difference between actual price and the equivalent single-period price.

We show that f is an equilibrium if and only if f must satisfies the constraints given by R1 or R2. We proceed with the analysis of two cases.

Case (i) Suppose that last inequality of R1 is satisfied. That is,

$$\frac{(1-f)(\alpha T - 1)(\gamma - \alpha)}{(\gamma T - \alpha T + 1)\gamma} \geq \frac{(\alpha - 1)(n - 1)}{(n\alpha - \alpha + 1)n}$$

From Lemma 3 we know that if this inequality holds, the provider sets the second-period price

$$W_2 = m \frac{(\alpha T - 1)(\gamma - \alpha)}{(\gamma T - \alpha T + 1)\gamma}$$

to induce all the $(1-f)n$ 1-OEMs to adopt in the second period.

The two-period payoff of a T-OEM is

$$\pi_A = \frac{T}{\theta} - W_1 + \delta m \frac{T}{\gamma T} = \frac{1}{\theta - T + 1} - \Delta + \delta m \frac{1}{\gamma}$$

Similarly, the two-period payoff of a 1-OEM is

$$\pi_N = \frac{1}{\theta} + \delta \left[m \left(\frac{\alpha T}{\gamma T} \right) - W_2 \right] = \frac{1}{\theta} + \delta m \frac{1}{\gamma T - \alpha T + 1}$$

Now consider the payoffs to a T-OEM who switches to a not-adopt decision in the first period. From Lemma 4 if f decreases to $f - \frac{1}{n}$ the provider still wishes to induce only 1-OEMs to adopt in the second period. After the T-OEM switching his decision in first period the provider charges a new second-period price W'_2 that induces all the 1-OEMs to adopt αT . By Lemma 3, W'_2 is

$$W'_2 = m \left(\frac{\alpha T}{\gamma T - T + \alpha T} - \frac{1}{\gamma T - T + 1} \right)$$

Hence, the T-OEM's two-period payoff assuming he switches to a not-adopt decision in the first period is

$$\pi'_A = \frac{1}{\theta - T + 1} + \delta \left[m \left(\frac{\alpha T}{\gamma T - T + \alpha T} \right) - W'_2 \right] = \frac{1}{\theta - T + 1} + \delta m \frac{1}{\gamma T - T + 1}$$

Similarly, the payoff to a 1-OEM who changes his decision (to adoption) in the first period is:

$$\begin{aligned}\pi'_N &= \frac{T}{\theta + T - 1} - W_1 + \delta m \frac{T}{\gamma T - \alpha T + T} \\ &= \frac{T}{\theta + T - 1} - \left(\frac{T}{\theta} - \frac{1}{\theta - T + 1} \right) - \Delta + \delta m \frac{1}{\gamma - \alpha + 1}\end{aligned}$$

The necessary and sufficient conditions for f to be an equilibrium are:

$$\begin{aligned}\pi'_N &< \pi_N \\ \text{and } \pi'_A &< \pi_A\end{aligned}$$

which through algebra translate to the first two inequalities of (R1).

Case (ii) The last inequality in R2 is satisfied.

Lemma 3 dictates that if this condition holds the provider induces all the OEMs to adopt in the second period. The corresponding second-period price is

$$W_2'' = m \left(\frac{\alpha T}{n\alpha T} - \frac{T}{n\alpha T - T} \right)$$

The payoff of a T-OEM and 1-OEM are

$$\begin{aligned}\pi_A &= \frac{T}{\theta} - W_1 + \delta \left[m \left(\frac{\alpha T}{n\alpha T} \right) - W_2'' \right] = \frac{1}{\theta - T + 1} - \Delta + \delta m \frac{1}{n\alpha - \alpha + 1} \\ \text{and } \pi_N &= \frac{1}{\theta} + \delta m \frac{1}{n\alpha - \alpha + 1}\end{aligned}$$

Along the same lines as Case (i), we calculate the deviation payoffs for a T-OEM as

$$\pi'_A = \frac{1}{\theta - T + 1} + \delta m \frac{1}{n\alpha - \alpha + 1}$$

and for a 1-OEM as

$$\begin{aligned}\pi'_N &= \frac{T}{\theta + T - 1} - W_1 + \delta m \frac{1}{n\alpha - \alpha + 1} \\ &= \frac{T}{\theta + T - 1} - \left(\frac{T}{\theta} - \frac{1}{\theta - T + 1} \right) - \Delta + \delta m \frac{1}{n\alpha - \alpha + 1}\end{aligned}$$

The necessary and sufficient conditions for equilibrium are

$$\begin{aligned}\pi'_N &< \pi_N \\ \text{and } \pi'_A &\leq \pi_A\end{aligned}$$

which lead to the first two inequalities of R2.

We conclude from the two cases that for f to be an equilibrium, it is necessary and sufficient that f must satisfy inequalities of either R1 or R2. ■

Observation: Lemma 5 determined the adoption pattern f for an arbitrary price W_1 . However, Lemma 5 can also be viewed as follows - By charging the price $W_1(f) = \Delta + \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1}\right)$, where Δ satisfies the constraints of either R1 or R2, the technology provider can induce the fraction f to adopt in the first period. Notice, that with this interpretation, the supplier has no incentive to charge anything less than the highest possible Δ to induce a given f . That is, $\Delta = \delta m \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ in the case of R1 and $\Delta = 0$ in the case of R2. Next, we prove theorem 1.

Proof. Lemma 5 demonstrated that there are two possible equilibrium patterns corresponding to an arbitrary price W_1 - (i) A fraction f adopts in first period, and the remaining $(1-f)n$ 1-OEMs adopt in second period (corresponding to R1), and (ii) A fraction f adopts in first period, and all the OEMs adopt in second period (corresponding to R2). We call the first pattern the leap-frogging strategy and the second one the saturation strategy.

Leap-frogging:

Corresponding to a given fraction of adopters f in the first period, the technology provider in the second period would find it beneficial to sell to only the 1-OEMs (i.e. leap-frogging) iff $\left(\frac{(1-f)(\alpha T-1)(\gamma_f-\alpha)}{(\gamma_f T-\alpha T+1)\gamma_f} \geq \frac{(\alpha-1)(n-1)}{(n\alpha-\alpha+1)n}\right)$, that is $\Phi(f) \geq 0$, or $f \in F_1$

Furthermore, a premium Δ (or price $W_1 = \Delta + \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1}\right)$) can be found which achieves leap-frogging iff there is a Δ that makes f feasible for R1. That is, it necessary and sufficient that LOWER BOUND OF $\Delta \geq$ UPPER BOUND OF Δ . Algebra shows that this condition is equivalent to $\Psi(f) \geq 0$, or $f \in F_2$. Also notice from the observation made immediately after lemma 5 that $\Delta = \delta m \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ in this case.

Hence a leap-frogging equilibrium with f adopters in first period is feasible iff $f \in F_1 \cap F_2 = F$, and the corresponding first and second-period prices are

$$\begin{aligned} W_1^p(f) &= \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1}\right) + \delta m \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} \\ W_2^p(f) &= \frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \end{aligned}$$

and the corresponding revenue is given by $\pi_p = n f W_1^p + n(1-f)W_2^p$. Maximizing $\pi_p(f)$ with respect to f gives us $\pi_p^* = \max_{f \in F} \pi_p(f)$, the optimal leap-frogging revenue.

Saturation:

In this case $\Delta = 0$, and the corresponding prices are

$$\begin{aligned} W_1^a(f) &= \frac{1}{\theta_f} - \frac{1}{\theta_f - T + 1} \\ W_2^a &= \frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \end{aligned}$$

and the corresponding revenue is given by $\pi_a(f) = n[fW_1^a(f) + W_2^a]$. $\pi_a(f)$ is increasing in f , thus if the technology provider follows saturation strategy, she sell to all the OEMs in first period and the second period.

The corresponding first- and second-period prices for full adoption are

$$\begin{aligned} W_1^a &= \frac{1}{n} - \frac{1}{nT - T + 1} \\ W_2^a &= \frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \end{aligned}$$

and the corresponding revenue is $\pi_a(1) = \pi_a = nW_1^a + nW_2^a$

Hence the optimal strategy for the firm is evaluated by finding the maximum leap-frogging revenue and comparing the revenue with the saturation strategy. ■

Proof of Proposition 1

Theorem 1 states that the optimal pricing strategy has one of the two structures: leap-frogging, or saturation. The corresponding revenues are π_p and π_a . To show the existence of the threshold α_t , we need to show that $\pi_p(\alpha) > \pi_a(\alpha)$ for all $\alpha < \alpha_t$.

Suppose that $\alpha = 1$. Then

$$\begin{aligned} \pi_a(\alpha = 1) &= nW \\ \pi_p(\alpha = 1) &= n f^* W_1^p + n(1-f^*)W > nW \text{ since } W_1^p > W \end{aligned}$$

Hence, $\pi_p(\alpha = 1) > \pi_a(\alpha = 1)$

Suppose α becomes very large. Then

$$\begin{aligned} \pi_a(\alpha \rightarrow \infty) &= n\left(\frac{T}{nT} - \frac{1}{nT-T+1}\right) + 1.m \\ \pi_p(\alpha \rightarrow \infty) &< \begin{cases} n f^* \left(\frac{T}{n f^* T + n(1-f^*)} - \frac{1}{n f^* T - T + 1 + n(1-f^*)}\right) + 1.m & \text{if } f^* < 1 \\ n\left(\frac{T}{nT+n} - \frac{1}{nT-T+1}\right) & \text{if } f^* = 1 \end{cases} \end{aligned}$$

In either case ($f^* = 1$ or $f^* < 1$) $\pi_p(\alpha \rightarrow \infty) < \pi_a(\alpha \rightarrow \infty)$. Therefore there exists at least one crossing point for $\pi_p(\alpha)$ and $\pi_a(\alpha)$ which is the threshold α_t .

Next, this crossing point (threshold) α_t is shown to be unique by proving that the $\pi_a(\alpha) - \pi_p(\alpha)$ is non-decreasing. Lemma 6 gives sufficient conditions for the function $\pi_a(\alpha) - \pi_p(\alpha)$ to be non-decreasing, and then Lemma 7 proves the sufficient conditions in Lemma 6 are indeed satisfied.

Lemma 6 Consider a function $G(x, \lambda)$. If $G(x, \lambda)$ is increasing in x , then $\min_p G(x, \lambda)$ is increasing with x .

Proof. Consider $x_1 < x_2$, and let $\lambda^*(x) = \arg \min_\lambda G(x, \lambda)$. Then, $\min_p G(x_2, \lambda) = G(x_2, \lambda^*(x_2)) \geq G(x_1, \lambda^*(x_2)) \geq \min_p G(x_1, \lambda)$ ■

Lemma 7 $\{\pi_a(\alpha) - \pi_p(\alpha, f)\}$ is non-decreasing in α

Proof. $\frac{1}{n}(\pi_a(\alpha) - \pi_p(\alpha, f)) = (W_1 + W_2(\alpha)) - (fW_1(\alpha, f) + (1-f)W_2(\alpha, f))$. Hence,

$$\begin{aligned} \frac{1}{n} \frac{d}{d\alpha} (\pi_a(\alpha) - \pi_p(\alpha, f)) &= m \frac{n-1}{(n\alpha - \alpha + 1)^2} \\ &\quad - \frac{d}{d\alpha} f \left(\delta m \left(\frac{1}{\gamma_f} - \frac{1}{(T\gamma_f - T + 1)} \right) \right) \\ &\quad - \frac{d}{d\alpha} (1-f)m \left(\frac{\alpha}{\gamma_f} - \frac{1}{T\gamma_f - \alpha T + 1} \right) \\ &= m \frac{n-1}{(n\alpha - \alpha + 1)^2} + mf\delta \frac{n(1-f)}{(\gamma_f)^2} - mf\delta \frac{n(1-f)T}{(T\gamma_f - T + 1)^2} \\ &\quad + (1-f)m \left(\frac{\alpha n(1-f)}{\gamma_f^2} - \frac{n(1-f)T - T}{(T\gamma_f - \alpha T + 1)^2} \right) \\ &\quad - (1-f)m \frac{1}{\gamma_f} \end{aligned}$$

$$\begin{aligned} \text{First term} &= f\delta \frac{n(1-f)}{(\gamma_f)^2} - f\delta \frac{n(1-f)T}{(T\gamma_f - T + 1)^2} \\ &> f\delta \frac{n(1-f)}{(\gamma_f)^2} - f\delta \frac{n(1-f)}{T\gamma_f^2} \\ &= f\delta \frac{n(1-f)(T-1)}{T(\gamma_f)^2} \\ &> 0 \end{aligned}$$

$$\begin{aligned}
\text{Second term} &= \frac{n-1}{(n\alpha - \alpha + 1)^2} - (1-f)\frac{1}{\gamma_f} + (1-f)^2 n \left(\frac{\alpha}{\gamma_f^2} - \frac{T}{(T\gamma_f - \alpha T + 1)^2} \right) \\
&= \frac{n-1}{(n\alpha - \alpha + 1)^2} - n(1-f) \left(\frac{f}{\gamma_f^2} + \frac{(1-f)T}{(T\gamma_f - \alpha T + 1)^2} \right) \\
&> \frac{n-1}{(n\alpha - \alpha + 1)^2} - n(1-f) \left(\frac{T^2 f}{(T\gamma_f - \alpha T + 1)^2} + \frac{(1-f)T}{(T\gamma_f - \alpha T + 1)^2} \right) \\
&> \frac{n-1}{(n\alpha - \alpha + 1)^2} - n(1-f) \left(\frac{T^2 f}{(T\gamma_f - \alpha T + 1)^2} + \frac{(1-f)T}{(T\gamma_f - \alpha T + 1)^2} \right) \\
&= \frac{n-1}{(n\alpha - \alpha + 1)^2} - n(1-f)T \left(\frac{fT - f + 1}{(T\gamma_f - \alpha T + 1)^2} \right) \\
&\geq \left(\begin{array}{l} \frac{n-1}{(n\alpha - \alpha + 1)^2} \\ - \left(\frac{1}{4}\right) \frac{T}{(\alpha T - 1)^2 n} \end{array} \right) \text{ Obtained by maximizing with respect to } f \\
&\geq 0
\end{aligned}$$

Hence, $\frac{d}{d\alpha} (\pi_a(\alpha) - \pi_p(\alpha, f)) \geq 0$, and the lemma is proved. ■

Proof of Corollary 1

The proof of Proposition 1 shows that $\pi_p(\alpha = 1) > \pi_a(\alpha = 1)$, which completes the proof.

Proof of Proposition 2

Consider the first-period price $W_1^p(f, \alpha)$ under the leap-frogging strategy

$$\begin{aligned}
W_1^p(f, \alpha) &= \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} \right) + \delta.m. \frac{(T-1)(\gamma_f - 1)}{(T\gamma_f - T + 1)\gamma_f} \\
&> \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} \right) \\
&> \frac{1}{n} - \frac{1}{nT - T + 1} \\
&= W_1^a
\end{aligned}$$

That is the first-period price under the leap-frogging strategy is always higher than the first-period price under the saturation strategy. Further, Proposition 1 shows that the leap-frogging strategy is optimal when $\alpha < \alpha_t$. Combining the two results we get $W_1^*(\alpha_1) > W_1^*(\alpha_2)$ if $\alpha_1 < \alpha_t$, and $\alpha_2 > \alpha_t$.

The second-period price $W_2^p(f, \alpha)$ under the leap-frogging strategy

$$\begin{aligned} W_2^p(f, \alpha) &= m. \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right) \\ &> m. \left(\frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \right) \\ &= W_2^a(\alpha) \end{aligned}$$

Using this inequality ($W_2^p(f, \alpha) > W_2^a(\alpha)$) at $\alpha = \alpha_t^-$ and noting that $W_2^a(\alpha)$ is continuous, we get second-period price is decreasing and discontinuous at the threshold (i.e. $W_2^*(\alpha_t^-) > W_2^*(\alpha_t^+)$).

Proof of Proposition 3

We shall write the price or the profits as functions of δ and m only when required. To prove the sensitivity results, we shall use Topkis' theorem which characterizes the monotonicity of maximizers (or minimizers) in terms of the supermodularity (or submodularity) of functions (Theorem 6 in Topkis, 1978).

CLAIM 1: $\alpha_t(\delta, m)$ is a strictly increasing function of δ and of m

Proof. Since $\alpha_t(\delta, m)$ is the crossing point of $\pi_p(\delta, m)$ and $\pi_a(\delta, m)$, the propositions are proven if we show that $\pi_p(\delta, m) - \pi_a(\delta, m)$ is a strictly increasing function of δ and of m (for a rigorous proof of this statement see Lemma 8 below). We have

$$\pi_p(\delta, m) - \pi_a(\delta, m) = n \max_f [f W_1^p(f, \delta, m) + (1-f) W_2^p(f, m)] - n(W_1^a + W_2^a(m))$$

However, notice that $n \max_f [f W_1^p(f, \delta, m) + (1-f) W_2^p(f, m)] - n(W_1^a + W_2^a(m))$ is a strictly increasing function of δ , since $W_1^p(f, \delta, m) = \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} \right) + \delta m \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f - T + 1)\gamma_f}$ is a strictly increasing function of δ . Hence, $\pi_p(\delta, m, \alpha) - \pi_a(\delta, m, \alpha)$ is a strictly increasing function of δ . Therefore $\alpha_t(\delta, m)$ (solution to $\pi_p(\delta, m) = \pi_a(\delta, m)$) is a strictly increasing function of δ .

For the second part of the claim define $\Gamma(m) = f W_1^p(f, \delta, m) + (1-f) W_2^p(f, m) - W_2^a(m)$.

Then,

$$\begin{aligned} \pi_p(\delta, m) - \pi_a(\delta, m) &= n \max_f [f W_1^p(f, \delta, m) + (1-f) W_2^p(f, m)] - n(W_1^a + W_2^a(m)) \\ &= n \max_f [\Gamma(m)] - n(W_1^a) \end{aligned}$$

Hence, if $\Gamma(m)$ is strictly increasing in m , then $\pi_p(\delta, m) - \pi_a(\delta, m)$ must also be strictly increasing in m .

$$\begin{aligned}\Gamma(m) &= fW_1^p(f, \delta, m) + (1-f)W_2^p(f, m) - W_2^a(m) \\ &= \left(\begin{array}{l} f \cdot \delta \cdot m \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} + (1-f) \cdot m \cdot \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right) \\ -m \cdot \left(\frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \right) + \text{const} \end{array} \right) \\ &= m \left(\begin{array}{l} f \cdot \delta \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} + (1-f) \cdot \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right) \\ - \left(\frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \right) \end{array} \right) + \text{const}\end{aligned}$$

is increasing in m , since $(1-f) \cdot \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right) \geq \left(\frac{1}{n} - \frac{1}{n\alpha - \alpha + 1} \right)$ holds for the equilibrium to be subgame perfect (this is actually one of the constraints of $R2$). Hence $\Gamma(m)$ is increasing in m , which implies that $\pi_p(\delta, m) - \pi_a(\delta, m)$ is strictly increasing in m . Therefore $\alpha_t(\delta, m)$ is strictly increasing in m . ■

Lemma 8 Consider a function $G(x, \theta)$. Define a threshold $t(\theta)$ as : $t(\theta) = \max\{x : G(x, \theta) \geq 0\}$. If $G(x, \theta)$ is increasing in θ , then the threshold $t(\theta)$ is increasing in θ .

Proof. Let $\theta_1 < \theta_2$. $G(t(\theta_1), \theta_1) \geq 0$ (by definition of $t(\theta)$). Hence, $G(t(\theta_1), \theta_2) > 0$ (since $G(x, \theta)$ is increasing in θ and $\theta_2 > \theta_1$). This implies that $t(\theta_2) > t(\theta_1)$ (by definition of $t(\theta)$ as the highest x which satisfies $G(x, \theta) \geq 0$.) That is, $\theta_1 < \theta_2 \Rightarrow t(\theta_1) < t(\theta_2)$. ■

CLAIM 2: $f^*(\delta, m)$ is non-decreasing in δ and is non-increasing in m .

Proof. Since $f^*(\delta, m) = \arg \max_{f \in F} \{fW_1^p(f, \delta, m) + (1-f)W_2^p(f, m)\}$, to prove the claim it suffices to show that $fW_1^p(f, \delta, m) + (1-f)W_2^p(f, m)$ is supermodular in (f, δ) and submodular in (f, m) (Topkis' theorem).

From the definitions of $W_1^p(f, \delta, m)$ and $W_2^p(f, m)$ we observe that this is equivalent to showing the supermodularity of $\delta \cdot m \cdot f \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ with respect to (f, δ) , and the submodularity of $\delta \cdot m \cdot f \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} + (1-f)m \cdot \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$ with respect to (f, m) .

Which in turn is equivalent to showing that $f \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ is an increasing function of f , and $\delta \cdot f \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} + (1-f) \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$ is a decreasing function of f . Lemma 9 proves this.

Hence $f^*(\delta, m)$ is non-decreasing in δ and non-increasing in m . ■

Lemma 9 $f \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ is an increasing function of f , and $\delta \cdot f \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} + (1-f) \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$ is a decreasing function of f .

Proof. Let $\Theta_1(f) = f \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$. Then

$$\begin{aligned} \Delta\Theta_1(f) &= \left(f + \frac{1}{n} \right) \left(\frac{1}{\gamma - (\alpha - 1)} - \frac{1}{(T(\gamma - (\alpha - 1)) - T + 1)} \right) - f \left(\frac{1}{\gamma} - \frac{1}{(T\gamma - T + 1)} \right) \\ &= f \left(\frac{1}{\gamma - (\alpha - 1)} - \frac{1}{\gamma} \right) - f \left(\frac{1}{(T(\gamma - (\alpha - 1)) - T + 1)} - \frac{1}{(T\gamma - T + 1)} \right) + \\ &\quad \frac{1}{n} \left(\frac{1}{\gamma - (\alpha - 1)} - \frac{1}{(T(\gamma - (\alpha - 1)) - T + 1)} \right) \\ &= \left(\frac{(\alpha-1)T}{(T\gamma-T-T(\alpha-1)+1)(T\gamma-T+1)} + \frac{1}{n} \left(\frac{1}{\gamma-(\alpha-1)} - \frac{1}{(T(\gamma-(\alpha-1))-T+1)} \right) \right) \geq 0 \end{aligned}$$

Lemma 4 shows that $\Theta_2(f) = (1-f) \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right) = \frac{(1-f)(\alpha T - 1)(\gamma_f - \alpha)}{(\gamma_f T - \alpha T + 1)\gamma_f}$ is a decreasing function of f (Intuitively, it is the revenue made by the supplier by selling to $(1-f)n$ customers in the second period, and this increases with $(1-f)$ or equivalently decreases with f). Hence, $\Theta_2(f) + \delta * \Theta_1(f)$ is decreasing in f for sufficiently low δ . For the case of large δ (i.e., δ close to 1), it can be shown by brute-force differentiation of $\Theta_2(f) + \delta * \Theta_1(f)$ with respect to f that $\Theta_2(f) + \delta * \Theta_1(f)$ is decreasing in f (upon request detailed calculations are available from the authors).

■

CLAIM 3: $W_1(\delta, m)$ is strictly increasing in m , and $W_2(\delta, m)$ is strictly increasing in δ except perhaps at a finite number of points.

CLAIM 4: $W_2(\delta, m)$ is strictly increasing in δ and $W_1(\delta, m)$ is strictly increasing in m , except perhaps at a finite number of points.

Proof. To obtain the proof of these claims it is sufficient to observe that when m increases, $W_1^p(\delta, m)$ increases because of (a) a decrease in $f^*(\delta, m)$ and (b) an increase in second term (Δ term representing the premium) of $W_1^p(\delta, m)$.

Similarly when δ increases, $W_2^p(\delta, m)$ increases because of a decrease in $1 - f^*(\delta, m)$. ■

CLAIM 5: $\pi_s(\delta, m)$ is strictly increasing in m and is strictly increasing in δ .

Proof. Consider $m_1 < m_2$, and let the corresponding optimal fractions be f_1^* and f_2^* , revenues be $\pi_p^1(f = f_1^*)$ and $\pi_p^2(f = f_2^*)$, first-period prices be $W_1^1(f = f_1^*)$ and $W_1^2(f = f_2^*)$,

second-period prices be $W_2^1(f = f_1^*)$ and $W_2^2(f = f_2^*)$ respectively.

$$\begin{aligned}
\pi_p^2(f = f_2^*) &\geq \pi_p^2(f = f_1^*) \text{ since } f_2^* \text{ is the optimal fraction for market-size } = m_2 \\
&= n(W_1^2(f = f_1^*)f_1^* + W_2^2(f = f_1^*)(1 - f_1^*)) \\
&> n(W_1^1(f = f_1^*)f_1^* + W_2^1(f = f_1^*)(1 - f_1^*)) \text{ since } W_1 \text{ and } W_2 \text{ increases in } m \\
&= \pi_p^1(f = f_1^*)
\end{aligned}$$

Hence, the technology provider's revenue must be strictly increasing in m .

Similarly consider $\delta_1 < \delta_2$, and let the optimal fractions be $f_1 = f_1^*$ and $f_2 = f_2^*$ respectively. It can be seen that in the high discount rate case (i.e. δ_2), if the provider sells to the same fraction of OEMs as in the low discount factor case (i.e. $f_2 = f_1^*$), she can charge a higher price in the first period and same price as before in the second period. Hence, the revenue must again be strictly higher for the higher discount case. ■

CLAIM 6: $\pi_c(\delta, m)$ is decreasing in δ

Proof. Since the sum of payoffs of the supplier and all the OEMs is constant ($= 1 + m$), and since by claim 5 we have that the supplier revenues increase with δ , we conclude that the OEM revenues must decrease with δ . ■

Proof of Proposition 4

Theorem 1 determines the provider's profits under the leap-frogging strategy as the maximum over f of a linear function of δ (i.e. $\pi_s = \max_f \{\text{Linear function of } \delta\}$). Since f is a bounded discrete variable, this implies that the profits are convex in δ (since π_s is the maximum of a set of linear functions of δ and must necessarily be convex in δ). Also from claim 5 we know that the revenues are increasing in δ . By our definition of δ as the expected value of the discount factor (i.e $\delta = E[\delta(t)] = (1 - p)\delta(t_a) + p\delta(t_a + d)$), δ is linear and decreasing in p (the probability of delays). Hence, π_s is decreasing and convex in p .

Proof of Proposition 5

Counter-example to prove proposition 5 given in Figure 17

Proof of Proposition 6

From program 1 (given in the main text), we know that $\alpha^* = \arg \max_{\alpha \geq 1} \{\max(\pi_p(\alpha), \pi_a(\alpha)) - c(\alpha - 1)^2\}$. Since $c(\alpha)^2$ is supermodular in (c, α) , $\pi_p(\alpha) - c(\alpha - 1)^2$ is submodular in (c, α) .

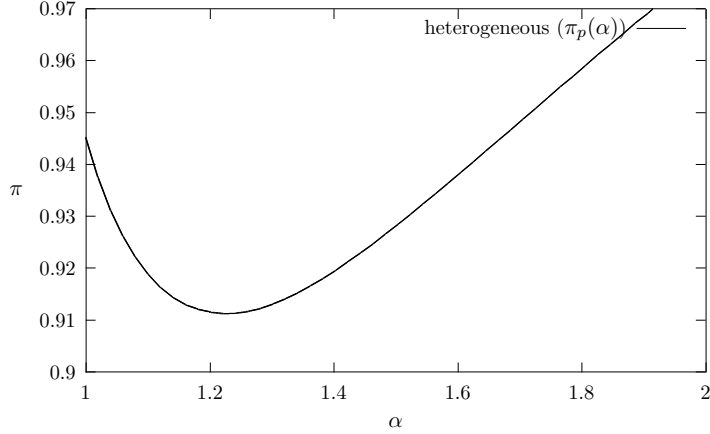


Figure 17: Supplier revenues as a function of α for the parameters $T = 2, n = 100, \delta = 0.9, m = 1$

Using Topkis' theorem, it follows that $\alpha^*(c)$ is decreasing in c in the region where provider undertakes leap-frogging strategy.

Proof of Proposition 7

Proposition 6 establishes that the optimal α^* is decreasing in c . Further, from Proposition 1 we know that if $\alpha^* \leq \alpha_t$, the technology provider would pursue leap-frogging strategy. Combining these results, we obtain that if the cost of development c is above a threshold c_t (corresponding to optimal development effort α_t), the technology provider would undertake a development effort $\alpha (< \alpha_t)$, and hence would choose leap-frogging strategy.

Proof of proposition 8

From program 1 (given in the main text), we know that $\alpha^* = \arg \max_{\alpha \geq 1} \{\pi_p(\alpha, \delta) - c(\alpha - 1)^2\}$ if the supplier follows leap-frogging strategy. Hence to prove that α^* is decreasing in δ it is sufficient to show that $\pi_p(\alpha, \delta)$ is submodular in (α, δ) (Topkis' theorem). Since $\pi_p(\alpha) = n[f^*W_1^p(f^*, \alpha, \delta, m) + (1 - f^*)W_2^p(f^*, \alpha, m)]$, this implies we need to show that $W_1^p(\cdot, \alpha, \delta, \cdot)$ is submodular in (α, δ) . Therefore we need to show that $W_1^p(\cdot, \alpha, \delta, \cdot) = \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1}\right) + \delta \cdot m \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ is submodular in (α, δ) , or equivalently that $\delta \cdot m \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ is submodular in (α, δ) , which is true since $\frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ is decreasing in α (Lemma 10).

Similarly, to show the monotonic increase of α^* with m we need to show that $\pi_p(\alpha, m)$ is supermodular in (α, m) (Topkis' theorem). Therefore we need to show that $\pi_p(\alpha, m) = n(fW_1^p(f, \alpha, \cdot, m) + (1 - f)W_2^p(f, \alpha, m))$ is supermodular in (α, m) , or equivalently that

$f \left(\delta m \cdot \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} \right) + (1-f)m \cdot \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$ is supermodular in (α, m) , which is true since $f \left(\delta \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} \right) + (1-f) \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$ is increasing in α (Lemma 11).

Lemma 10 $\frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f}$ is decreasing in α .

Proof. By our definition, $\gamma = nf + n(1-f)\alpha$, therefore it is sufficient to show that $\Theta_2(\gamma) = \left(\frac{1}{\gamma} - \frac{1}{(T\gamma-T+1)} \right) = \frac{(T-1)(\gamma-1)}{(T\gamma-T+1)\gamma}$ is decreasing in γ . Taking the derivative with respect to γ we get

$$\begin{aligned} \Theta_2'(\gamma) &= \left(-\frac{1}{\gamma^2} + \frac{T}{(T\gamma-T+1)^2} \right) \\ &= -\frac{(T(\gamma-1)^2-1)(T-1)}{(T\gamma-T+1)\gamma} \\ &< 0 \end{aligned}$$

■

Lemma 11 $f \left(\delta \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} \right) + (1-f) \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$ is increasing in α .

Proof. Let $\Theta_3(\alpha) = f \left(\delta \frac{(T-1)(\gamma_f-1)}{(T\gamma_f-T+1)\gamma_f} \right) + (1-f) \left(\frac{\alpha}{\gamma_f} - \frac{1}{\gamma_f T - \alpha T + 1} \right)$. Also let $\mu = \gamma'(\alpha) = n(1-f)$ Then

$$\begin{aligned} \Theta_3'(\alpha) &= \delta \left(-\frac{1}{\gamma^2} + \frac{T}{(T\gamma-T+1)^2} \right) + \left(\frac{1}{\gamma} - \frac{\alpha}{\gamma^2} \mu + \frac{\mu T - T}{(\gamma T - \alpha T + 1)^2} \right) \\ &\geq \left(-\frac{1}{\gamma^2} + \frac{T}{(T\gamma-T+1)^2} \right) + \left(\frac{nf}{\gamma^2} + \frac{\mu T - T}{(\gamma T - \alpha T + 1)^2} \right) \\ &\geq 0 \end{aligned}$$

■

As the first extension, we consider the case of upgrade prices. For technology markets which have upgrade prices, we show that the equilibrium solutions retain their basic structure (as well as many of the secondary results as the basic model).

This game differs from the no-upgrade price game only in the 4th stage. At the beginning of the second period (4th stage), the technology provider prices the second-period technology αT at W_2 if the adopting OEM is a 1-OEM, and at $W_2 - u$ if the adopting OEM is a T-OEM. A summary of the proof is given next before proceeding with the formal proof.

Summary of Proof of theorem 1'

The structure of the proof follows that of Theorem 1. To highlight the similarities, the auxillary lemmas are numbered similarly. For instance Lemma 2' for Theorem 1' is similar to Lemma 2 for Theorem 1.

Lemma 2' outlines the necessary and sufficient conditions for an arbitrary number of αT adopters to be an equilibrium. Intuitively, the number of adopters (both from the T-OEMs and from the 1-OEMs) is such that the increase in revenues for the marginal adopter ("last" adopter) is balanced out by the price paid for the technology.

Lemma 3' demonstrates that, in the second period, the technology provider sells technology αT to all the T-OEMs (at an upgrade discount), **and** to all the 1-OEMs.

Then, Lemma 5' gives the adoption behavior of the OEMs in the first period for any arbitrary first-period price W_1 . Lemma 5' can also be interpreted as determining the price W_1 which induces an arbitrary adoption pattern.

Next, we formulate a mathematical program to determine the number of first-period adopters the technology provider would induce. Finally, Proposition 19 demonstrates that the optimal fraction of adopters is increasing with technology enhancement. Hence, the technology provider would induce partial adoption in the first period if and only if the technology enhancement is below a threshold.

Formal Proof of theorem 1'

Lemma 2' *Given any history $\{W_1, f, W_2, u\}$ at the fifth stage, let n_p is the number of T-OEMs who adopted again in second period, an n_q is the number of 1-OEMs who adopted in second period. Then, (p, q) is an equilibrium iff*

$$\left(\frac{\alpha T}{\beta_{p,q} + \alpha T - 1} - \frac{1}{\beta_{p,q}} \right) m < W_2 \leq \left(\frac{\alpha T}{\beta_{p,q}} - \frac{1}{\beta_{p,q} - \alpha T + 1} \right) m$$

and

$$\left(\frac{\alpha T}{\beta_{p,q} + \alpha T - T} - \frac{T}{\beta_{p,q}} \right) m < W_2 - u \leq \left(\frac{\alpha T}{\beta_{p,q}} - \frac{T}{\beta_{p,q} - \alpha T + T} \right) m$$

where

$$\beta_{p,q} = (f - p)Tn + np\alpha T + ((1 - f) - q)n + nq\alpha T$$

Proof. If (p, q) is an equilibrium, then none of the 1-OEMs must have an incentive to switch their second-period decisions, that is

$$\begin{aligned} m \frac{\alpha T}{\beta_{p,q}} - W_2 &\geq m \frac{1}{\beta_{p,q} - \alpha T + 1} \\ \text{and } m \frac{\alpha T}{\beta_{p,q} + \alpha T - 1} - W_2 &< m \frac{1}{\beta_{p,q}} \\ \Rightarrow \left(\frac{\alpha T}{\beta_{p,q} + \alpha T - 1} - \frac{1}{\beta_{p,q}} \right) m &< W_2 \leq \left(\frac{\alpha T}{\beta_{p,q}} - \frac{1}{\beta_{p,q} - \alpha T + 1} \right) m \end{aligned}$$

Similarly, for the T-OEMs, equilibrium dictates that

$$\begin{aligned} m \frac{\alpha T}{\beta_{p,q}} - W_2 + u &\geq m \frac{T}{\beta_{p,q} - \alpha T + T} \\ \text{and } m \frac{\alpha T}{\beta_{p,q} + \alpha T - T} - W_2 + u &< m \frac{T}{\beta_{p,q}} \\ \Rightarrow \left(\frac{\alpha T}{\beta_{p,q} + \alpha T - T} - \frac{T}{\beta_{p,q}} \right) m &< W_2 - u \leq \left(\frac{\alpha T}{\beta_{p,q}} - \frac{T}{\beta_{p,q} - \alpha T + T} \right) m \end{aligned}$$

■

Lemma 3' *Given any history $\{W_1, f\}$, it is optimal for the technology provider to set a price (W_2, u) where*

$$\begin{aligned} W_2 &= m \left(\frac{1}{n} - \frac{1}{n\alpha T - \alpha T + 1} \right) \\ u &= m \left(\frac{1}{n\alpha - \alpha + 1} - \frac{1}{n\alpha T - \alpha T + 1} \right) \end{aligned}$$

such that at the corresponding equilibrium all the T-OEMs and all the 1-OEMs adopt technology αT .

Proof. Let $\pi(p, q)$ be the revenues accrued by the technology provider by setting the price (W_2, u) such that the equilibrium induced is (p, q) . Then,

$$\begin{aligned} \pi(p, q) &= p(W_2 - u) + qW_2 \\ &= p \left(\frac{\alpha T}{\beta_{p,q}} - \frac{T}{\beta_{p,q} - \alpha T + T} \right) m + q \left(\frac{\alpha T}{\beta_{p,q}} - \frac{1}{\beta_{p,q} - \alpha T + 1} \right) m \end{aligned}$$

Then,

$$\begin{aligned}
\frac{1}{m} \frac{\partial \pi}{\partial p} &= \left(\frac{\alpha T}{\beta_{p,q}} - \frac{T}{\beta_{p,q} - \alpha T + T} \right) + p \left(-\frac{\alpha T}{\beta_{p,q}^2} (\alpha - 1) T + \frac{T}{(\beta_{p,q} - \alpha T + T)^2} (\alpha - 1) T \right) + \\
&\quad q \left(-\frac{\alpha T}{\beta_{p,q}^2} (\alpha - 1) T + \frac{1}{(\beta_{p,q} - \alpha T + 1)^2} (\alpha - 1) T \right) \\
&= \left(\frac{\alpha T}{\beta_{p,q}} - \frac{T}{\beta_{p,q} - \alpha T + T} \right) - (\alpha - 1) T \left(\frac{p\alpha T + q\alpha T}{\beta_{p,q}^2} - \frac{pT + q}{(\beta_{p,q} - \alpha T + 1)^2} \right) \\
&= \left(\frac{\alpha T}{\beta} - \frac{T}{\beta - \alpha T + T} \right) - (\alpha - 1) T \left(\frac{p\alpha T + q\alpha T}{\beta^2} - \frac{pT + q}{(\beta - \alpha T + 1)^2} \right) \\
&\geq \left(\frac{\alpha T}{\beta} - \frac{T}{\beta - \alpha T + T} \right) - (\alpha - 1) T \left(\frac{n\alpha T}{\beta^2} \right) \\
&= \frac{(\beta^2 - Tn\alpha\beta - T\alpha\beta - T^2n\alpha + T^2n\alpha^2) (\alpha - 1) T}{(\beta + T - T\alpha) \beta^2} \\
&\geq 0
\end{aligned}$$

Similarly, it can be shown that $\frac{\partial \pi}{\partial q} \geq 0$. Hence, $\pi(p, q) < \pi(p+1, q)$ and $\pi(p, q) < \pi(p, q+1)$, and the technology provider can always gain higher revenues by increasing p or q . That is the maximum for $\pi(p, q)$ would be attained at the boundary, i.e. at $p = f$, and $q = 1 - f$. Substituting these maximizing values into the expression for W_2 and u , the lemma is proved.

■

Lemma 5' *Corresponding to a first-period price W_1 , f is an equilibrium iff*

$$\frac{T}{\theta_f + T - 1} - \frac{1}{\theta_f} < W_1 - \delta m \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \leq \frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1}$$

Proof. Consider the payoff π_A of a first-period adopter, and let π'_A be his payoff if he switches to a not-adopt decision in the first period. Then,

$$\begin{aligned}
\pi_A &= \frac{T}{\theta_f} - W_1 + \delta m \left(\frac{T}{n\alpha T - \alpha T + T} \right) \\
\pi'_A &= \frac{1}{\theta_f - T + 1} + \delta m \left(\frac{1}{n\alpha T - \alpha T + 1} \right)
\end{aligned}$$

Similarly, let π_N be the payoff of a first-period non-adopter, and let π'_N be his payoff if he switches to an adopt decision in the first period. Then,

$$\begin{aligned}
\pi_N &= \frac{1}{\theta_f} + \delta m \left(\frac{1}{n\alpha T - \alpha T + 1} \right) \\
\pi'_A &= \frac{T}{\theta_f + T - 1} - W_1 + \delta m \left(\frac{T}{n\alpha T - \alpha T + T} \right)
\end{aligned}$$

For f to be an equilibrium, it is necessary and sufficient that

$$\pi_A \geq \pi'_A$$

$$\pi_N > \pi'_N$$

That is

$$\begin{aligned} W_1 &\leq \frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} + \delta m \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \\ W_1 &> \frac{T}{\theta_f + T - 1} - \frac{1}{\theta_f} + \delta m \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \end{aligned}$$

■

Next, we formulate a mathematical program to determine the optimal fraction of adopters in the first period induced by the technology provider.

$$\begin{aligned} f^*(\alpha) &= \arg \max_f \{\pi_p(f)\} = \arg \max_f \{W_1(f)nf + (W_2 - u)nf + W_2n(1 - f)\} \\ &= \arg \max_f \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} + \delta m \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \right) nf + \\ &\quad nf \left(\frac{1}{n} - \frac{T}{n\alpha T - \alpha T + T} \right) m + \\ &\quad n(1 - f) \left(\frac{1}{n} - \frac{1}{n\alpha T - \alpha T + 1} \right) m \\ &= \arg \max_f \left\{ \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} - m(1 - \delta) \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \right) f \right\} \end{aligned}$$

The corresponding prices and revenues are given by

$$\begin{aligned} W_1 &= \frac{T}{\theta_{f^*}} - \frac{1}{\theta_{f^*} - T + 1} + \delta m \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \\ W_2 &= m \left(\frac{1}{n} - \frac{1}{n\alpha T - \alpha T + 1} \right) \\ u &= m \left(\frac{1}{n\alpha - \alpha + 1} - \frac{1}{n\alpha T - \alpha T + 1} \right) \\ \pi &= \left(\frac{T}{\theta_{f^*}} - \frac{1}{\theta_{f^*} - T + 1} - m(1 - \delta) \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \right) nf^* \\ &\quad + \left(1 - \frac{n}{n\alpha T - \alpha T + 1} \right) m \end{aligned}$$

Proposition 19 $f^*(\alpha)$ is a non-decreasing function of α .

Proof. Since $f^*(\alpha) = \arg \max_f \left\{ \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} - m(1 - \delta) \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \right) f \right\}$,

for the proposition to be true, it is sufficient that

$\left\{ \left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} - m(1 - \delta) \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) \right) f \right\}$ is supermodular in (f, α) (Topkis' theorem). Hence, it is sufficient that $\left(\frac{T}{\theta_f} - \frac{1}{\theta_f - T + 1} \right) f$ is supermodular in (f, α) , and $-m(1 - \delta) \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) f$ is supermodular in (f, α) . $-m(1 - \delta) \left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right) f$ is evidently supermodular in (f, α) since $-\left(\frac{T}{n\alpha T - \alpha T + T} - \frac{1}{n\alpha T - \alpha T + 1} \right)$ is increasing function of α . For the second part, it is again supermodular since it is independent of α . Hence, it is proved that f^* is non-decreasing in α . ■

A number of secondary results relating to the dependence of optimal introduction strategy on m , δ , and α can be obtained. We summarize them in the following table. These results, are identical to the ones in Proposition 3 suggesting that the basic insights developed in the no-upgrade case are robust and applicable to this new setting. Proofs of these results are available upon request.

		δ or $-p$	m	α
CLAIM 2'	f^*	\nearrow	\searrow	\nearrow
CLAIM 3'	W_1	\nearrow	\nearrow	\searrow
CLAIM 4'	W_2	<i>constant</i>	\nearrow	\nearrow
CLAIM 4''	u	<i>constant</i>	\nearrow	\searrow
CLAIM 5'	π_s	\nearrow	\nearrow	-
CLAIM 6'	π_c	\searrow	-	-

Proof of Observation 1

Technology Enhancing Capabilities : Consider an OEM with capability κ who employs technology τ . His revenues are given by $\frac{\kappa\tau}{D}$ where D is the denominator term representing the total quality in the market. Switching to technology T ($T > \tau$) implies

$$\begin{aligned}
\text{Marginal Benefit } \Delta(\kappa) &= \frac{\kappa T}{D - \kappa\tau + \kappa T} - \frac{\kappa\tau}{D} \\
\implies \frac{d\Delta(\kappa)}{d\kappa} &= \frac{(D^2 - 2D\kappa\tau + \kappa^2\tau^2 - \kappa^2T\tau)(T - \tau)}{D(D + \kappa T - \kappa\tau)^2} > 0
\end{aligned}$$

Hence, for technology enhancing capabilities, H OEMs (who have capability $\kappa = \kappa_h$) have higher marginal benefit than L OEMs (who have capability $\kappa = 1$).

Technology Independent Capabilities: Consider an OEM with capability κ who employs technology τ . His revenues are given by $\frac{\kappa+\tau}{D}$ where D is the denominator term representing

the total quality in the market. Switching to technology T ($T > \tau$) implies

$$\begin{aligned}\text{Marginal Benefit } \Delta(\kappa) &= \frac{\kappa + T}{D - (\kappa + \tau) + (\kappa + T)} - \frac{\kappa + \tau}{D} \\ \implies \frac{d\Delta(\kappa)}{d\kappa} &= -\frac{T - \tau}{D(D - \tau + T)} < 0\end{aligned}$$

Hence, for technology enhancing capabilities, H OEMs (who have capability $\kappa = \kappa_h$) have lower marginal benefit than L OEMs (who have capability $\kappa = 0$).

APPENDIX B

SUPPLEMENT TO CHAPTER III

The payoffs to the (row player) OEMs after successful integration is as given in Table 5. For instance, the cell $\{SUCCESS, FAIL\}$ denotes the payoffs ($=b$) to the row-player when outcome of his integration is success, and the outcome of his competitor's integration process is failure.

For ease of notation, let $p_C = p_C(T)$ and $p_I = p_I(f)$. Table 6 gives the joint distribution of the outcome of the integration effort. For instance, the probability of the row-player succeeding while his competitor fails his integration is given by the value in cell $\{SUCCESS, FAIL\} = p_C p_I (1 - p_I)$.

Based on Tables 5 and 6, we may evaluate the expected payoffs to OEMs conditional on their adoption decisions (i.e, decisions whether or not to license the component). Table 7 gives this expected payoffs (to the row player). For instance, the value in the cell $\{A, N\}$ denotes the expected payoffs to the row-player when he decides to adopt the component whereas his competitor decides not to adopt it.

Table 5: Payoffs (to row player) after integration

	<i>SUCCESS</i>	<i>FAIL</i>
<i>SUCCESS</i>	<i>a</i>	<i>b</i>
<i>FAIL</i>	<i>c</i>	<i>d</i>

Table 6: Joint Probabilities of integration outcomes

	<i>SUCCESS</i>	<i>FAIL</i>
<i>SUCCESS</i>	$p_C p_I^2$	$p_C p_I (1 - p_I)$
<i>FAIL</i>	$p_C (1 - p_I) p_I$	$p_C (1 - p_I)^2 + (1 - p_C)$

Proof of Proposition 9

Table 8 gives the net (expected) payoffs (i.e., payoffs - license-fee). The proof is easily

Table 7: Expected Payoffs (to the row player)

	A	N
A	$p_C \left(\begin{array}{l} p_I^2 a \\ + p_I (1 - p_I) b \\ + (1 - p_I) p_{Ic} \\ + (1 - p_I)^2 d \end{array} \right) + (1 - p_C)d - C(f)$	$p_C \left(\begin{array}{l} p_I b \\ + (1 - p_I) d \end{array} \right) + (1 - p_C)d - C(f)$
N	$p_C \left(\begin{array}{l} p_{Ic} \\ + (1 - p_I) d \end{array} \right) + (1 - p_C)d$	d

Table 8: Net Expected Payoffs (to the row player)

	A	N
A	$p_C \left(\begin{array}{l} p_I^2 a \\ + p_I (1 - p_I) b \\ + (1 - p_I) p_{Ic} \\ + (1 - p_I)^2 d \end{array} \right) + (1 - p_C)d - C(f) - W$	$p_C \left(\begin{array}{l} p_I b \\ + (1 - p_I) d \end{array} \right) + (1 - p_C)d - C(f) - W$
N	$p_C \left(\begin{array}{l} p_{Ic} \\ + (1 - p_I) d \end{array} \right) + (1 - p_C)d$	d

deduced from direct examination of the table.

Proof of Corollary 2

The provider's revenues under saturation strategy is

$$\begin{aligned}
\pi_s &= 2(W_s - C) \\
&= p_C(p_I F - p_I^2(F - S)) \text{ where } F = b - d \text{ and } S = a - c \\
&= p_C(p_I(f)F - p_I(f)^2(F - S)) \\
\frac{\partial \pi_s}{\partial f} &= p_C \frac{\partial p_I(f)}{\partial f} (F - 2p_I(f)(F - S)) \\
&< 0 \text{ iff } p_I(f) > \frac{F}{2(F - S)} \\
&\implies \pi_s(f) \text{ is decreasing if } f > p_I^{-1} \left(\frac{F}{2(F - S)} \right)
\end{aligned}$$

Before proving Theorem 2, we state and prove the following auxilliary lemma.

Lemma 12 *For an arbitrary function $F(x)$, let $N(F)$ be the number of roots of the equation $F(x) = 0$. If $F(x)$ is twice differentiable and convex and $N(F) < \infty$, then, $N(F) \leq 2$.*

Proof. Suppose the equation has more than 2 roots. Let x_1, x_2, x_3 be 3 of the roots such that $x_1 < x_2 < x_3$ and there are no roots between x_1 and x_2 and between x_2 and x_3 . By mean value theorem, we know that there exists an $x_{12} \in (x_1, x_2)$ such that $\frac{F(x_2)-F(x_1)}{x_2-x_1} = F'(x_{12})$. However, $F(x_2) = F(x_1) = 0$. Hence, there exists an $x_{12} \in (x_1, x_2)$ such that $F'(x_{12}) = 0$. Similarly, there exists an $x_{23} \in (x_2, x_3)$ such that $F'(x_{23}) = 0$.

$F(x)$ is convex, hence $F''(x) \geq 0$. Thus, $F'(x)$ is non-decreasing. That is, for any $x < y$, $F'(x) \leq F'(y)$. We know that there exists $x_{12} \in (x_1, x_2)$ and $x_{23} \in (x_2, x_3)$ such that $F'(x_{12}) = F'(x_{23}) = 0$. Hence, for all $x \in [x_{12}, x_{23}]$ $F'(x) = 0$. That is, $F(x)$ is constant in the interval $[x_{12}, x_{23}]$. Since $x_2 \in (x_{12}, x_{23})$ and $F(x_2) = 0$, this means that for all $x \in [x_{12}, x_{23}]$, $F(x) = 0$. However, this is a contradiction since we assumed that there are no roots between x_1, x_2, x_3 . ■

Proof of Theorem 2

The profits under the saturation and niche strategy are given by π_s and π_n respectively where

$$\begin{aligned}\pi_n &= p_C p_I (b - d) - C \\ \pi_s &= 2(p_C (p_I (b - d) - p_I^2 ((b - d) - (a - c))) - C)\end{aligned}$$

For ease of notation, let

$$\begin{aligned}F &= b - d \\ S &= a - c\end{aligned}$$

Then, the provider adopts saturation strategy iff $\pi_s \geq \pi_n$ and $\pi_s \geq 0$. The first condition is equivalent to

$$\begin{aligned}2(p_C (p_I F - p_I^2 (F - S)) - C) &> p_C p_I F - C \\ \text{i.e. } 2p_C p_I^2 (F - S) - p_C p_I F + C &< 0\end{aligned}$$

Define the function

$$G(p_I) = p_C (2p_I^2 (F - S) - p_I F) + C$$

Thus, the saturation strategy is superior to niche strategy iff $G(p_I) \leq 0$.

$(2p_I^2(F - S) - p_I F)$ is convex in p_I . Suppose, $C(p_I^{-1}(x))$ is convex in x . (This assumption allows ease of exposition. See the note at the end of the proof how this assumption can be eliminated relatively easily.) Hence, $G(p_I)$ is convex. Thus, by Lemma 12 it has at most two roots. These roots give the two critical thresholds critical values of p_I at which the strategy switches between saturation and niche. Also note that for very low values of p_I , (for instance $p_I \approx 0$), $G(p_I) > 0$ and it is optimal to use the niche strategy. Thus, there exists p_1 and p_2 (defined by the roots of $G(p_I) = 0$) such that for saturation strategy is superior to niche strategy only if $p_1 \leq p_I \leq p_2$.

It is optimal to use the niche strategy instead of not-selling iff $p_C p_I F - C > 0$. Thus, there exists a threshold p_0 (since $p_C p_I (b - d) - C$ is increasing in p_I) such that niche adoption is superior to not-selling iff $p_I \geq p_0$. At this threshold $G(p_I = p_0) = p_C (2p_0^2(F - S) - p_0 F) + C = 2p_C p_0^2(F - S) > 0$. Hence, at $p_I = p_0$ niche is superior to saturation, thus giving us that $p_0 \leq p_1$. It can be verified that saturation strategy (for $p_1 \leq p_I \leq p_2$) is always superior to no-sale since (i) saturation is superior to niche in this region, and (ii) niche is superior to no-sale in this region (since $p_I \geq p_1 \geq p_0$).

Thus the existence of the three threshold p_0, p_1, p_2 are established for the probabilities of integration success p_I . The equivalent thresholds on f are given by $f_0 = p_I^{-1}(p_0)$, $f_1 = p_I^{-1}(p_1)$, $f_2 = p_I^{-1}(p_2)$.

The proof for thresholds for the technologies is very similar, and a brief sketch is provided below. Let

$$\begin{aligned} G(T) &= p_C (2p_I^2(F - S) - p_I F) + C \\ &= p_I p_C (2p_I(F - S) - F) + C \end{aligned}$$

By assumption **A1**, $b(T)$ is concave in T , hence $F(T) = b(T) - d$ is concave in T , hence $-F$ is convex in T . Furthermore, by assumption **A4**, $F - S$ is convex in T . Similarly by assumption C is convex in T . Hence, $G(T)$ is convex in T and has at most two roots. As before, there exists also a region such that no sale occurs. Thus the existence of three thresholds for the technology T is also proved.

Note: We assumed that $C(p_I^{-1}(x))$ is convex in x . Now suppose $C(p_I^{-1}(x))$ is concave in x ,

then $p_I(C^{-1}(x))$ is convex in x , and thresholds for C (say C_0, C_1, C_2) can be found that are equivalent to the thresholds p_0, p_1, p_2 we used in the proof provided earlier.

Proof of Proposition 10

Case 1: $f_0(T)$ is non-increasing in T .

To prove this, consider $T_2 > T_1$ and assume the converse, i.e., let $f_0(T_2) > f_0(T_1)$. Choose any $f \in (f_0(T_1), f_0(T_2))$. Since $f > f_0(T_1)$, the point $[f, T_1]$ cannot be in the no-sale region. Since $f < f_0(T_2)$, the point $[f, T_2]$ must be in the no-sale region. Thus, there exists an f such that as T increases (i.e., we go from T_1 to T_2 where $T_2 > T_1$), we switch into no-sale region from saturation or niche region. This is obviously false by Theorem 2. Hence, $f_0(T_2) \leq f_0(T_1)$ for all $T_2 > T_1$, that is $f_0(T)$ is non-increasing

The proofs for the sensitivity of all other thresholds are similar and not shown.

Proof of Proposition 11.(A)

Table 9: Net Expected Payoffs (to the row player) when fixed-fees + volume-based license fees are used

	A	N
A	$p_C \left(\begin{array}{l} p_I^2(a - D_a w) \\ + p_I(1 - p_I)(b - D_b w) \\ + (1 - p_I)p_I c \\ + (1 - p_I)^2 d \end{array} \right) + (1 - p_C)d - C(f) - W$	$p_C \left(\begin{array}{l} p_I(b - D_b w) \\ + (1 - p_I)d \end{array} \right) + (1 - p_C)d - C(f) - W$
N	$p_C \left(\begin{array}{l} p_I c \\ + (1 - p_I)d \end{array} \right) + (1 - p_C)d$	d

Table 9 gives the net (expected) payoffs (i.e., payoffs - (demand \times per-unit-fee + license-fee)). Examination of the table reveals that $\{A, A\}$ (i.e., saturation) is an equilibrium iff

$$p_C \left(\begin{array}{l} p_I^2(a - D_a w) \\ + p_I(1 - p_I)(b - D_b w) \\ + (1 - p_I)p_I c \\ + (1 - p_I)^2 d \end{array} \right) + (1 - p_C)d - C(f) - W > p_C \left(\begin{array}{l} p_I c \\ + (1 - p_I)d \end{array} \right) + (1 - p_C)d$$

which simplifies to

$$p_C (p_I^2 D_a w + p_I(1 - p_I) D_b w) + W \leq p_C (p_I F(w) - p_I^2 (F(w) - S(w))) - C$$

Similarly, the necessary and sufficient condition for $\{A, N\}$ (or $\{N, A\}$) to be an equilibrium

can be easily written down from looking at Table 9. These conditions are

$$p_C p_I D_b w + W \leq p_C p_I F(w) - C$$

Proof of Proposition 11.(B)

Case 1: Suppose the provider uses the saturation strategy with license fees $[W, w]$. Then, her expected revenue is

$$\begin{aligned} \pi_s &= 2W + p_C(p_I^2(2wD_a) + p_I(1 - p_I)(wD_b) + (1 - p_I)p_I(wD_b)) \\ &= 2(W + p_C(p_I^2 D_a w + p_I(1 - p_I)D_b w)) \end{aligned}$$

From Proposition 11.(B) we know that under saturation strategy

$$(W + p_C(p_I^2 D_a w + p_I(1 - p_I)D_b w)) < p_C(p_I F(w) - p_I^2(F(w) - S(w))) - C.$$

Thus, the maximum revenues the provider can obtain is given by

$$\pi_s = 2 \max_w \{p_C(p_I F(w) - p_I^2(F(w) - S(w))) - C\}$$

Notice that the maximizing value of $w (= w^*)$ gives the optimal per-unit license-fee for the saturation strategy, and the optimal value of fixed-fee is given by W such that

$$(W + p_C(p_I^2 D_a w^* + p_I(1 - p_I)D_b w^*)) = p_C(p_I F(w^*) - p_I^2(F(w^*) - S(w^*))) - C.$$

Case 2: Now suppose the provider uses niche strategy with license fees $[W, w]$. Then, her expected revenue is

$$\begin{aligned} \pi_n &= W + p_C p_I D_b w \\ &\leq p_C p_I F(w) - C \text{ from Proposition 11.(A)} \end{aligned}$$

Thus, the maximum revenues the provider obtains under the niche strategy is given by $\max_w p_C p_I F(w) - C$. Since $F(w) = b(w) - d$ is decreasing in w (by assumption **A5.1**), the maximizing value is $w = 0$. Thus, the provider does not use per-unit license-fees under the niche strategy and her optimal profits are given by

$$\pi_n = p_C p_I F(w = 0) - C$$

Proof of Corollary 3

The proof follows directly from Proposition 11.(B) by observing that the per-unit volume-based royalty is present only under the saturation strategy and never under the niche strategy.

Proof of Theorem 3

The thresholds on f are proved first. From Proposition 11.(B) we know that the revenues under saturation strategy

$$\pi_s = 2p_C \max_w \{p_I F(w) - p_I^2(F(w) - S(w))\} - C$$

and the revenues under niche strategy is

$$\pi_n = p_C p_I F(w = 0) - C$$

Consider the function

$$\begin{aligned} G(p_I, w) &= p_C p_I F(w = 0) - C - (2p_C(p_I F(w) - p_I^2(F(w) - S(w))) - C) \\ &= p_C p_I F(w = 0) + C - 2p_C(p_I F(w) - p_I^2(F(w) - S(w))) \end{aligned}$$

As in Theorem 2, it can readily be shown that $G(p_I, w)$ is convex in p_I and thus has only two roots. Let the corresponding values of f be $f_1(w)$ and $f_2(w)$. That is, $G(p_I(f_1(w)), w) = 0$ and $G(p_I(f_2(w)), w) = 0$. Furthermore, for any f at which saturation strategy is optimal, there must exist a w such that $f_1(w) \leq f \leq f_2(w)$,

Consider two arbitrary values for f , say f' and f'' at which the saturation strategy is superior to niche strategy. Then, exists w' and w'' such that

$$\begin{aligned} f_1(w') &\leq f' \leq f_2(w') \\ f_1(w'') &\leq f'' \leq f_2(w'') \end{aligned}$$

Without loss of generality, suppose $f' < f''$. To prove that the saturation region is optimal for any $f \in (f', f'')$, it suffices to prove that there exists \hat{w} such that

$$f_1(\hat{w}) \leq f \leq f_2(\hat{w})$$

Also, note that $f_2(w)$ is continuous¹.

¹The continuity of $f_1(\cdot)$ and $f_2(\cdot)$ may be verified by observing that $F(\cdot)$ and $S(\cdot)$ are continuous and differentiable.

Case 1: $f_2(w') \geq f$

Then, w' satisfies the requirement since $f_1(w') \leq f' \leq f \leq f_2(w')$

Case 2: $f_2(w') < f$

Since $f' \leq f_2(w') < f < f'' \leq f_2(w'')$, and since $f_2(\cdot)$ is continuous, there exists a $\hat{w} \in [w', w'']$ such that $f_2(\hat{w}) = f$. Furthermore, $f_1(\hat{w}) \leq f_2(\hat{w})$. Hence, this \hat{w} satisfies the requirement as $f_1(\hat{w}) \leq f = f_2(\hat{w})$. Thus, it is proved that for any $f \in [f', f'']$ we again follow the saturation strategy. This implies that the new thresholds where we follow the saturation strategy is given by $f_1 = \min_w f_1(w)$ and $f_2 = \max_w f_2(w)$. The threshold f_0 is evaluated as in Theorem 2 since under the niche strategy volume-based royalty are suboptimal and the results remain identical.

The proof for the threshold on T is identical and is available from the authors.

Proof of Proposition 12

The proof mirrors the proof of Proposition 10 and is available from the authors.

Proof of Proposition 13

From Proposition 11.(B), we know that the optimal volume-based royalty under saturation strategy is given by

$$w^* = \arg \max_w \{F(w) - p_I(F(w) - S(w))\}$$

Consider an arbitrary f' for which it is optimal not to charge any volume-based royalties (i.e., $w = 0$). Then,

$$F(w) - p_I(f')(F(w) - S(w)) \leq F(0) - p_I(f')(F(0) - S(0))$$

Furthermore, it can be easily verified that when $p_I(f = 0) = 0$ it is optimal not to charge any volume-based royalties (since $F(w) = b(w) - d$ is decreasing in w). That is,

$$F(w) - 0(F(w) - S(w)) \leq F(0) - 0(F(0) - S(0))$$

Thus, for any $f < f'$

$$\left(\begin{array}{l} \frac{p_I(f)}{p_I(f')} \{F(w) - p_I(f')(F(w) - S(w))\} \\ + \left(1 - \frac{p_I(f)}{p_I(f')}\right) \{F(w) - 0(F(w) - S(w))\} \end{array} \right) \leq \left(\begin{array}{l} \frac{p_I(f)}{p_I(f)} \{F(0) - p_I(f')(F(0) - S(0))\} \\ + \left(1 - \frac{p_I(f)}{p_I(f)}\right) \{F(0) - 0(F(0) - S(0))\} \end{array} \right)$$

i.e., $F(w) - p_I(f)(F(w) - S(w)) \leq F(0) - p_I(f)(F(0) - S(0))$. Hence, no volume-based royalties will be charged for any $f < f'$ either. Thus, there exists a threshold f_v such that volume-based royalties are optimal iff $f \geq f_v$.

Proof of Proposition 14

K is the complexity of the interfaces, and $p_I = p_I(f, K)$ where $p_I(f, K)$ is decreasing in K , increasing in f , and submodular in (f, K) . As in the proof of Theorem 2, we may find the thresholds p_0, p_1, p_2 . Notice that these thresholds do not involve K . However, the equivalent thresholds f_0, f_1, f_2 depend on K . Since $p_I(f, K)$ is decreasing in K , the equivalent thresholds are all increasing in K . Thus, the region $[0, f_0]$ (which is the no-sale region) increases in K .

To prove that the saturation region becomes larger with K , we need to show that $f_2 - f_1$ is increasing in K . Define the (inverse) function $f(p, K)$ such that $p = p_I(f(p, K), K)$ (i.e., $f(p, K)$ is the inverse function defined for a specific value of p and K). To prove our claim about saturation region increasing, it is sufficient to show that $f(p_2, K) - f(p_1, K)$ is increasing in K . This is true if $f(p, K)$ is supermodular. That is $\frac{\partial^2 f}{\partial p \partial K} \geq 0$

$$\begin{aligned} \frac{\partial^2 f}{\partial p \partial K} &= \frac{\partial}{\partial K} \left(\frac{\partial f}{\partial p} \right) \\ &= \frac{\partial}{\partial K} \left(\frac{1}{\frac{\partial p}{\partial f}} \right) \\ &= -\frac{1}{\left(\frac{\partial p}{\partial f}\right)^2} \frac{\partial^2 p}{\partial f \partial K} \geq 0 \text{ since } p_I(f, K) \text{ is submodular, i.e., } \frac{\partial^2 p}{\partial f \partial K} \leq 0 \end{aligned}$$

Thus, $f_2 - f_1$ is increasing in K and the saturation-region becomes larger with K .

Finally, since both saturation and no-sale region become larger with K , it must necessarily be true that niche-region becomes smaller with K .

APPENDIX C

SUPPLEMENT TO CHAPTER IV

Proof of Theorem 4

If no contract is signed till the end of 2^{nd} period, then the joint value that can be obtained through a contract is $MV(P_{A1} + \eta_{A1} + P_{A2} + \eta_{A2}, P_{B1} + \eta_{B1} + P_{B2} + \eta_{B2})$. Hence, whoever proposes the contract will take the entire pie leaving the other party no alternative than to accept the contract. Since the probability of being the proposer is $\frac{1}{2}$, the expected profits is given by

$$\frac{1}{2}MV(P_{A1} + \eta_{A1} + P_{A2} + \eta_{A2}, P_{B1} + \eta_{B1} + P_{B2} + \eta_{B2})$$

Thus looking ahead from the beginning of period 2, the firms see that if a contract is not signed then, the profits would be given by the nash-equilibrium of the game where the payoffs are given by

$$u(x, y) = E \left[\frac{1}{2}(m + \epsilon_1 + \epsilon_2)V(P_{A1} + \eta_{A1} + x + \eta_{A2}, P_{B1} + \eta_{B1} + y + \eta_{B2}) \right] - c(x)$$

Let these equilibrium values be $u(x^*, y^*)$.

However, if a contract is signed at the beginning of period 2, the total value that can be generated is given by

$$\Pi = \max_{x, y} \{E[(m + \epsilon_1 + \epsilon_2)V(P_{A1} + \eta_{A1} + x + \eta_{A2}, P_{B1} + \eta_{B1} + y + \eta_{B2})] - c(x) - c(y)\}$$

It can be seen that an acceptable contract exists iff $\Pi \geq 2u(x^*, y^*)$ since without this the minimum feasible allocation without contract may be obtained by not signing right away. Some algebra verifies that this condition is always satisfied, hence the contract is always signed at the end of period 1 if not signed sooner and the theorem is proved.

Proof of Theorem 5

Suppose the contract is signed before development. Then, the total value generated is given by

$$\Pi = \max_{x_1, x_2, y_1, y_2} \left\{ \begin{array}{l} E[(m + \epsilon_1 + \epsilon_2)V(x_1 + \eta_{A1} + x_2 + \eta_{A2}, y_1 + \eta_{B1} + y_2 + \eta_{B2})] \\ -c(x_1) - c(y_1) - c(x_2) - c(y_2) \end{array} \right\}$$

It can be seen that Π is independent of the variance of ϵ_1 and ϵ_2 (since Π is linear in the random variables).

The existence of thresholds can be established if we can show that the value of delaying the contract till end of 1st period is increasing in the variance of ϵ_1 . By Theorem 4, the value of delaying the contract till end of period 1 is given by the nash equilibrium of the game with payoffs

$$u(x, y; \sigma) = \frac{1}{2} E \left[\max_{\alpha, \beta} \left\{ \begin{array}{l} E[(m + \sigma\epsilon + \epsilon_2)V(x + \eta_{A1} + \alpha + \eta_{A2}, y + \eta_{B1} + \beta + \eta_{B2})] \\ -c(\alpha) - c(\beta) \end{array} \right\} \right] - c(x)$$

It can be shown relatively easily that this game is supermodular in (x, y) and is also supermodular in the parameter (i.e., $u(x, y; \sigma)$ is supermodular in (x, σ) and (y, σ)). Thus, the value is increasing in σ (as an aside, it also emerges that the initial effort levels $x^* = P_{A1}$ and $y^* = P_{B1}$ are increasing in σ). Thus the existence of thresholds on σ are established.

Proof of Propositions 16 and 17

The value of the project is the greater of the following two values: value when the contract is delayed till end of period 1, or value when the contract is signed upfront. From the proof of Theorem 5 we know that the value of the project when the contract is delayed till end of period 1 is increasing in the uncertainty σ . Furthermore, we have also shown that the value of project when contract is signed upfront is independent of the uncertainty (i.e., is constant). Thus, the maximum of these two values must be non-decreasing in the uncertainty (σ) and the proposition is proved.

Proof of proposition 18

The value of contract when signed in first period itself is

$$\begin{aligned}\Pi &= \max_{x,y,a,b} \left\{ \begin{array}{l} E[(m + \epsilon_1 + \epsilon_2)(x + \eta_{1A} + a + \eta_{2A} + y + \eta_{1B} + b + \eta_{2B})] \\ -cx^2 - cy^2 - ca^2 - cb^2 \end{array} \right\} \\ &= \frac{m^2}{c}\end{aligned}$$

The value of contract when signed at end of first period is

$$\begin{aligned}\Pi(x, y) &= \max_{a,b} \left\{ \begin{array}{l} E[(m + \epsilon_1 + \epsilon_2)(x + \eta_{1A} + a + \eta_{2A} + y + \eta_{1B} + b + \eta_{2B})] \\ -ca^2 - cb^2 \end{array} \right\} \\ &= (m + \sigma\epsilon) \left(x + \eta_{1A} + y + \eta_{1B} + 2\frac{m + \sigma\epsilon}{2c} \right) - 2c \left(\frac{m + \sigma\epsilon}{2c} \right)^2\end{aligned}$$

Thus, expected value when putting in efforts x and y is

$$\begin{aligned}E[\Pi(x, y)] &= m(x + y) + E \left[\frac{(m + \sigma\epsilon)^2}{2c} \right] \\ &= m(x + y) + \frac{m^2}{2c} + \frac{\sigma^2}{2c}\end{aligned}$$

Thus, the payoffs of the game when no contract is signed in first period is given by

$$u(x, y) = \frac{1}{2} \left(m(x + y) + \frac{m^2}{2c} + \frac{\sigma^2}{2c} \right) - cx^2$$

Thus, at equilibrium $x^* = y^* = \frac{m}{4c}$, and the equilibrium payoffs are

$$\Pi_{contract} = \frac{7m^2 + 4\sigma^2}{16c}$$

Thus a contract is signed before the project iff

$$\frac{m^2}{c} \geq 2\frac{7m^2 + 4\sigma^2}{16c} \text{ i.e., } \frac{\sigma}{m} \leq \frac{1}{2}$$

Thus, the proposition is proved.

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