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Time-Consuming Technology Development: How Imitation and Spillovers affect Competitive Dynamics

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Abstract

While there is an extensive body of theory on R&D, the literature predominantly focuses on the uncertain nature of *research* activities. In contrast, we study the time-consuming and costly, but more certain, process of technology *development*. We analyze the effect of imitation and the resulting knowledge spillovers from technology leaders to technology followers on competitive dynamics such as the rate of technology diffusion in an industry, the sustainability of technology-based competitive advantages, and performance differences across firms. Our results challenge the widely accepted view that inter-firm spillovers are beneficial to technology followers but detrimental to technology leaders. We show that leaders may have incentives to increase spillovers to induce followers to switch from concurrent to imitative technology development strategies. Conversely, follower firms may be worse off with more spillovers because leaders expect to be imitated faster and have fewer incentives to develop a new technology, which delays its diffusion into the industry. In addition, we characterize the incentives of technology leaders and followers to invest in development capabilities. Our model derives testable relationships between important competitive and financial variables that are often empirically observable.

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1. Introduction

The research and development of new technologies by profit-seeking firms is central to the evolution of industries and to the broader economy. There is an extensive body of theory in industrial organization on research activities, where the defining feature of research is that the outcomes associated with effort are uncertain as in, for example, the literature on patent races (Reinganum, 1981a; Judd, 1985). However, after research results in a technology breakthrough there usually remains a time-consuming and costly period of development before the new technology can be deployed into a market. In practice, development activities can make up a significant fraction of the total time and costs associated with R&D (Mansfield, 1971). For example, after the emergence of powerful new internet technologies in the mid 1990s, economic activity was only transformed after thousands of incumbent and startup firms completed costly and time-consuming development projects aimed at exploiting the new technologies in a variety of industries such as financial services, travel agency and general retail.[1] Despite the economic importance of such time consuming and costly development activities - and in marked contrast to research activities - the formal theory of technology development is largely... undeveloped.

There is an existing theoretical literature on technology adoption where firms decide when to purchase a new technology (e.g. Fudenberg and Tirole, 1985 and Riordan, 1992; see Hoppe, 2002, for a survey), which we see as related to, but distinct from, technology development. We model technology development using two central features of adoption models. First, we incorporate a tradeoff between time-to-market and the cost of acquiring a new technology. Second, we follow the adoption literature in specifying the effects of the technology on product-market competition: acquiring the technology increases a firm's flow of profits from the market and weakly decreases the profit flow of competitors. The main source of differences is that in our theory the time-cost tradeoff arises endogenously from a costly and time consuming development process internal to each firm, whereas in the adoption literature this tradeoff is exogenously given by price reductions coming from (un-modeled) dynamics in an upstream industry supplying the new technology.

Each firm engaging in its own time-consuming development process, rather than simply

[1] During its first four years of development, the online retailer Amazon.com spent a reported $800 million on web site development, payment processing systems, warehouse operations and customer service software (Leschly et al., 2003).

purchasing the technology from a supplier, has important implications. There is now a question of how firms sequence their development activities. One possibility is that firms run concurrent development processes. Another possibility is that some firms take an imitative approach in which they wait to start their own development until a technology leader has completed development and deployed the technology in the market. The use of such imitative strategies gives rise to the possibility of spillovers (Mansfield., 1985; Cassiman and Veugelers, 2002) from technology leaders to followers. We model spillovers as serving to make the follower's development problem easier so that they face a more favorable time-cost tradeoff. We also allow time-cost tradeoffs to vary across firms due to differences in development capabilities. Differences in organizational capabilities are rarely captured in formal models, but constitute a central concern in the management and strategy literatures (Sutton, 2005).

We study the competitive interactions among firms that are developing and deploying a new technology into product markets. We characterize how the equilibrium time-to-market of technology leaders and technology followers depends on a variety of factors including the underlying complexity of the technology, whether followers engage in concurrent or imitative development, and the extent of spillovers from technology leaders to imitators. We show that the leader's competitive advantage from earlier access to the technology always results in superior performance under concurrent development, but not necessarily when its competitor imitates. In addition, we obtain rather surprising results on the effect of spillovers on firm profits. Our findings challenge the widely accepted view that inter-firm spillovers are beneficial to technology followers but detrimental to technology leaders (Mansfield, 1985; Cassiman and Veugelers, 2002). We show that a technology leader may be better off when some of its technical knowhow freely flows to followers and that followers may have an incentive to reduce the amount of knowhow that they are able to appropriate from technology leaders.

The paper proceeds as follows. Section 2 motivates the central elements of our theory in the context of technology development in the microprocessor industry. Section 3 specifies and discusses the formal model. Section 4 characterizes equilibrium time-to-market for both imitative and concurrent development. Section 5 considers prior literature, especially the literature on technology adoption. We analyze the effect of imitation on time-to-market, firm profits, and the incentives to invest in capabilities in sections 6, 7, and 8, respectively. The key results on endogenous spillovers can be found in Section 7.1. Section 9 concludes with suggested avenues for further investigation.

2. A Motivating Example: The Microprocessor Industry

Our theory is well motivated by competition to develop microprocessors for use in personal computers. The microprocessor industry has produced a series of significant new product introductions, with performance roughly doubling every 18 months in accordance with the prediction of Moore's Law. Product development is very time consuming. For example, the Federal Trade Commission estimated in 1997 that the development of a state-of-the-art microprocessor such as the Pentium II took at least four years (Pitofsky et al., 1998). Significant and increasing levels of resources have gone into the development of microprocessors. Already in the 1980s, Intel's development of the 80386 processor reportedly cost $200 million (Casadesus-Masanell et al. 2005). The microprocessor industry is then a classic setting with costly and time-consuming development activities. Our interest is in the nature of the competitive interactions that arise in such settings.[2]

The PC microprocessor industry has effectively been a duopoly for much of its history. Intel Corporation has usually played the role of technology leader in that it usually is the first to introduce next-generation products to the market. Advanced Micro Devices (AMD) has usually played the role of a follower. At first, AMD's strategy was explicitly one of imitation: it waited until Intel released its processors and then developed its own products based on Intel's specifications. For the first two product generations, the 8086 and the 80286, AMD benefited from high spillovers due to a cross-licensing agreement with Intel. Even with access to Intel's intellectual property (IP), AMD still faced time-consuming technology development; for example AMD was two years behind Intel when it launched its version of the 80286 in 1984.

With the development of the 80386 in 1985, Intel sought to reduce spillovers to AMD, largely by refusing to license its designs. An Intel lawyer would later claim "we don't have any barriers for competitors, just a few speed bumps that people have to go around" (Casadesus-Masanell et al. 2005, p. 11). With the need to now reverse-engineer Intel's chips and with the increasing complexity of the technology, AMD was over five years

[2] We are indebted to Scott Stern for the microprocessor industry example. Events in the industry are widely documented, with Shih and Ofek (2007) containing a recent summary.

behind Intel in bringing an 80386 product to market. AMD proved more capable with the 80486, but it was still four years behind Intel by the time it launched its version in 1993. During this period, AMD sued Intel to enforce the original cross-licensing agreement. Although AMD ultimately won damages for generations up to the 80486, it had become clear that AMD would not have access to Intel's IP for subsequent generations.

In response to the reduced spillovers from Intel, AMD ultimately dropped its strategy of imitative development. Instead, AMD started pursuing a strategy of concurrent development where they designed their own next generation processors at the same time as Intel was working on theirs. While AMD succeeded in bringing out its own next generation designs, including the K5 and K6, Intel retained its position as the technology leader.[3] Nonetheless, there was concern that AMD's shift in strategy from imitative to concurrent development was having an adverse effect on Intel's profitability (see, for example, "The Monkey and the Gorilla" in *The Economist*, December 5, 1998 pp. 71-72).

Many of the features of competition in the microprocessor market are common to other industries. Numerous consumer electronics markets like digital cameras, mp3 players and cell phones exhibit costly and time-consuming new product development. As with microprocessors, there are regular new product introductions (mp3 players with greater storage capacity, digital cameras with higher mega pixels and cell phones with new features) without high degrees of technological uncertainty. Like Intel, there are some firms in these markets that consistently play the role of technology leaders (e.g. Sony, Apple and Samsung) while many others are followers (e.g. Matsushita, many Chinese firms). In terms of the timing of firm development activities, one again observes both concurrent development of a given technology generation by multiple firms as well as extensive reverse-engineering activities by firms pursuing imitative development strategies.

3. The Model

We consider an industry with two competing firms that face an opportunity to develop a new technology. We index the firms by $i = 1, 2$. Firm profits are given by the present value of their revenues from the product market net of the present value of their technol-

[3] After its shift to concurrent development, AMD has at times sought to challenge Intel's role as technology leader. See, for example, "AMD to Intel: Let's Rumble" in *BusinessWeek*, August 23, 2005. However, Intel has remained the dominant firm with a market capitalization that has consistently remained significantly greater than AMD's.

ogy development costs for a common discount rate (or cost of capital) given by r. We restrict attention to parameter values such that both firms find it profitable to develop the technology.

The model is in continuous time indexed by $t \geq 0$. We denote the time at which firm i completes development of the new technology by $T_i \geq 0$, which we refer to as firm i's time-to-market. We focus on games and equilibria in which the firms have clear expectations as to the order in which firms complete development. As a convention, we can then take $T_1 \leq T_2$ so that firm 1 is the technology leader (if there is one) and firm 2 is the follower.

Firms are homogeneous except along two dimensions. First, firms may differ in their development capabilities. We model such capabilities as shifting a firm's time-cost tradeoff (i.e., for a fixed level of expenditures, a more capable firm develops faster). Second, we assume that one firm has a pre-existing reputation as a technology leader while the other firm has a reputation as a follower. These reputations determine the roles firms play. Endogeneizing these roles is certainly of interest, but lies beyond the scope of this paper.

3.1. Product Market Competition

Firms receive revenue flows from the product market. Firm's are equally competitive absent asymmetries that arise when one firm has completed development but the other firm has not. When neither firm has completed development, each firms' revenue flows are π_{00}, while when both firms have completed development, they have revenue flows of π_{11}. When just one firm has completed development, the firm with the new technology has revenue flows of π_{10} while the disadvantaged firm has revenue flows of π_{01}. We assume that these revenue flows satisfy $\pi_{10} > \pi_{11} > \pi_{00} \geq \pi_{01} \geq 0$ so that developing the new technology enhances a firm's revenue flows while decreasing those of its competitor. The case of a new market, where the technology is required to have positive revenue flows, is a special case of our model where $\pi_{00} = \pi_{01} = 0$.

With $T_1 \leq T_2$, we have that the present value of revenues for the leader is

$$R_1(T_1, T_2) = \int_0^{T_1} \pi_{00} e^{-rt} dt + \int_{T_1}^{T_2} \pi_{10} e^{-rt} dt + \int_{T_2}^{\infty} \pi_{11} e^{-rt} dt, \tag{3.1}$$

while the present value of the follower's revenues is

$$R_2(T_1, T_2) = \int_0^{T_1} \pi_{00} e^{-rt} dt + \int_{T_1}^{T_2} \pi_{01} e^{-rt} dt + \int_{T_2}^{\infty} \pi_{11} e^{-rt} dt. \qquad (3.2)$$

It is useful to define $\Delta_1 \equiv \pi_{10} - \pi_{00}$, the increase in revenue flows for the first firm to market with the new technology, and $\Delta_2 \equiv \pi_{11} - \pi_{01}$, the increase in revenue flows for the second firm to market. As is common in the literature, we assume that $\Delta_1 > \Delta_2$ (e.g., Reinganum, 1981b; Fudenberg and Tirole, 1985). In the new market case, where the new technology is required to have any revenue flows, this restriction is just a requirement that the profits of a monopolist (π_{10}) are greater than the profits of a duopolist (π_{11}).

3.2. Technology Development by a Firm

Development of the technology requires a firm to exert effort over time and we assume that there are decreasing returns to effort at a point of time.[4] The assumption of decreasing returns is important because it gives rise to a tradeoff between the cost of development and the firm's time-to-market. Such a time-cost tradeoff goes back to early work on technology development (Scherer, 1967; Mansfield, 1968). The time cost tradeoff is given by the function $C(T; Z_i)$. The parameter $Z_i > 0$ gives the total effort required for firm i to develop the technology, which depends on the complexity of the technology relative to firm i's development capabilities.

We derive the function $C(T; Z_i)$ from the following explicit development process. Let $c_i(t) \geq 0$ be the expenditures profile that gives firm i's flow of cost of development at each time t. Expenditures translate into effort at a rate $\sqrt{c_i(t)}$, which incorporates decreasing returns to instantaneous expenditures.[5] The present value of development costs for a given T and Z_i is

$$C(T; Z_i) = \int_0^{T_i} c_i^*(t; T, Z_i) e^{-rt} dt,$$

where $c_i^*(t; T, Z_i)$ is the expenditure profile that minimizes the net present value of development costs subject to the constraint that all effort is exerted by the completion time

[4] One can interpret the level of effort as the number of engineers (and other resources) allocated to technology development. There are decreasing returns to effort, for example, if engineers have to spend an increasing fraction of their time coordinating their activities as the size of the development team grows.

[5] One can model decreasing returns more generallly as $(c_i(t))^\alpha$ for $\alpha \in (0, 1)$; see Pacheco de Almeida and Zemsky (2007). However, this formulation is much less tractable for the comparisons of interest in this paper.

(i.e., $\int_0^T \sqrt{c_i(t)}dt = Z_i$).[6]

3.3. Two Development Games

As in the microprocessor industry, we consider two scenarios for the timing of firms' development activities. One possibility is that development activities are sequential so that one firm completes development before the other commences. In this case, we allow the follower firm to benefit from spillovers, which serve to reduce (but not eliminate) the total effort Z_2 required to develop the technology. We refer to this scenario as imitative development. In the other scenario, the firms engage in concurrent development where they are both actively developing the technology at the same time. For the case of concurrent development, we assume that there are no significant inter-firm spillovers. Note that with concurrent development there can still be a technology leader if one firm commits greater resources to development and thereby completes its technology development first.

Concurrent Development

With concurrent development, both firms start their development activities at time $t = 0$. The total effort required for each firm to develop the technology in this game are

$$\begin{aligned} Z_1 &= (1 - d_1)K, \\ Z_2 &= (1 - d_2)K. \end{aligned}$$

The parameter $K > 0$ reflects the underlying complexity of the technology. The parameters d_1 and d_2 reflect each firm's capability for developing the new technology and are restricted to $d_i \in [0, 1)$. Capability differences between the firms could reflect either differences in a general capability for developing new technologies or they could reflect prior development experiences that facilitate development of this particular new technology.

Since the work of Fudenberg and Tirole (1985), it is standard in the literature to solve for closed-loop equilibria where firms can costlessly vary their strategies over time.[7] This is essentially a requirement of subgame perfection. However, Ruiz-Aliseda and Zemsky (2007) show that open-loop equilibria in our concurrent development game can satisfy sub-

[6] This model of technology development was first proposed by Lucas (1971), who solves the monopoly case. Other papers building on Lucas (1971) are Grossman and Shapiro (1986) who generalize the analysis and Toxvaerd (2007) who incorporates an agency problem.

[7] The adoption literature had originally focused on open-loop equilibria where firms committed to development times at the start of the game as in Reinganum (1981b) and Quirmbach (1986).

game perfection and that the rent-equalizing equilibria identified by Fudenberg and Tirole (1985) break down. The key difference with adoption models is that with development firms are incurring expenses continuously over time. In this paper, we simply assume that firms are playing an open-loop equilibria in that they commit to a $c_i(t)$ expenditure profile at time $t = 0$ and we then solve for pure strategy Nash equilibria. We discuss our solution concept and how it relates to prior work in greater detail in Section 5.

We make two restrictions on the parameters. To assure that both firms have an incentive to develop the new technology, we assume that

$$\sqrt{\Delta_i} > rZ_i \text{ for } i = 1, 2. \tag{A1}$$

While we can allow for the possibility that the follower is more capable than the leader (i.e., $d_2 > d_1$), we need to limit the extent of such asymmetries. Otherwise, it is not possible to support an equilibrium where firm 1 develops first. Specifically, we assume that

$$(1 - d_2)\sqrt{\Delta_1} > (1 - d_1)\sqrt{\Delta_2}. \tag{A2}$$

As $\Delta_1 > \Delta_2$, any $d_1 \geq d_2$ satisfies inequality (A2) and the more that Δ_1 exceeds Δ_2, the more that d_2 can exceed d_1.

Imitative Development

With imitative development, the firms develop sequentially, with the follower starting its development process when the leader finishes. Thus, the leader's development process runs from time $t = 0$ until time $t = T_1$ and the follower is exerting effort from time $t = T_1$ until time $t = T_2$. This game would arise, for example, if firm 1 were uniquely aware of the opportunity to develop the new technology and firm 2 only became aware of it when firm 1 deploys the technology to the market.[8]

Although imitation delays the start of firm 2's development, it potentially allows the firm to benefit from spillovers from the leader. We assume that

$$\begin{aligned} Z_1 &= (1 - d_1)K, \\ Z_2^I &= (1 - s)(1 - d_2)K. \end{aligned}$$

[8] Imitative development could also be a choice by firm 2 as discussed in Section 7.1.

The parameters $d_i \in [0, 1)$ and K are as in the concurrent game. The parameter s reflects the extent to which the follower benefits from spillovers under imitative development. One would generally expect s to be higher for product innovations, which tend to be visible to customers and competitors and can be reverse engineered, than for process innovations, which tend to be less visible externally. The leader's effort Z_1 is the same across both games.

We are taking a novel approach to modeling knowledge spillovers. The standard approach follows Spence (1984) where marginal costs are a function of firm R&D expenses and spillovers are modeled as a negative relationship between a firm's marginal costs and the R&D expenditures of other firms (see, for example, Levin and Reiss 1988; Leahy and Neary, 1997; Ceccagnoli, 2005). In contrast to the reduced-form approach in the received literature, spillovers in our model do not directly impact a firm's marginal costs. Rather, spillovers serve to reduce the time-cost tradeoff for imitating firms.

Given the sequential structure of imitative development, it is natural to solve the imitation game for subgame perfect equilibria. That is, firm 2's strategy is optimal given the observable development time of firm 1 and firm 1 takes into account the optimal development strategy of firm 2 in choosing its own development time.

Condition (A1) is not sufficient to assure that the leader develops in this game. A sufficient condition to assure that firm 1 develops is:[9]

$$\sqrt{\pi_{11} - \pi_{00}} > rZ_1. \tag{A3}$$

We assume that (A1)-(A3) hold throughout the paper.

4. Equilibrium Characterization

We now solve for the equilibrium time-to-market in the two development games. Recall that firms choose their time-to-market so as to maximize the net present value of their revenues from the product market net of their technology development costs. We have that the present value of revenues for firm i are given by $R_i(T_1, T_2)$. The first step in the analysis is to derive an expression for $C(T, Z_i)$, which will then give us a closed-form expression for firm payoffs.

[9] The follower finds it profitable to develop *iff* $\sqrt{\Delta_2} > rZ_2^I$ but this is implied by (A1) as $Z_2 \geq Z_2^I$.

4.1. Cost Minimizing Technology Development

For a given completion time, the cost minimizing expenditure profile is determined by the following tradeoff. On the one hand, the decreasing returns to instantaneous expenditures favors spreading effort uniformly over time. On the other hand, discounting favors shifting expenditures towards the end of the development period. We have the following result, originally shown by Lucas (1971).

Lemma 4.1. *Suppose that firm i seeks to develop the new technology over the interval of time $[0, T]$. The cost minimizing expenditure profile for a given level of total effort Z_i is*

$$c^*(t; T, Z_i) = \left(\frac{r Z_i e^{rt}}{e^{rT} - 1} \right)^2 .$$

The minimized cost of technology development is then

$$C(T; Z_i) = \frac{r Z_i^2}{e^{rT} - 1}.$$

The cost minimizing expenditure profile is increasing over time and it depends on the cost of capital. The cost function is a decreasing, convex function of the development time T and an increasing, convex function of the total effort Z_i.

4.2. Firm Payoffs

We can now state closed form expressions for firm payoffs. For concurrent development, we have that firm payoffs are given by

$$\Pi_i^C = R_i(T_1, T_2) - C(T_i; Z_i) \text{ for } i = 1, 2.$$

With imitative development, the follower develops over the interval $[T_1, T_2]$ and hence payoffs in this case are

$$\begin{aligned} \Pi_1^I &= R_1(T_1, T_2) - C(T_1; Z_1), \\ \Pi_2^I &= R_2(T_1, T_2) - e^{-rT_1} C(T_2 - T_1; Z_2^I). \end{aligned}$$

The discounting of $C(T_2 - T_1; Z_2^I)$ arises because the cost function $C(T;Z)$ gives the present value of development costs at the start of development, which is T_1 for the follower, while firm payoffs are discounted back to $t = 0$.

An attractive feature of our model is that there are closed form expressions for the optimal time-to-market. It is useful to illustrate by solving for the optimal time-to-market when only a single firm is developing the technology. Suppose that firm 2 does not develop (i.e., $T_2 = \infty$) and let $Z_1 = Z$ and $\Delta_1 = \Delta$. The payoff of the single developing firm is then $\Pi(T) = R_1(T,\infty) - rZ^2/(e^{rT} - 1)$. There is a unique solution to the first order condition $\Pi'(T) = 0$, given by

$$T^* = \frac{1}{r}\ln(1 - \frac{rZ}{\sqrt{\Delta}})^{-1}.$$

If $rZ < \sqrt{\Delta}$, then the firm maximizes its payoff by developing at time $T = T^*$, while if $rZ \geq \sqrt{\Delta}$, then T^* is not a real number and the firm's payoff is maximized at $T = \infty$ (i.e., non development). The greater the required effort Z, the longer the firm optimally takes for development, while the greater the flow of benefits to deploying the technology Δ, the faster is development. All the equilibrium development times in our model have the same functional form as T^* with only the value of Z and Δ changing across firms and games.[10]

4.3. Equilibrium Development Times

We now solve for the equilibrium development times in each of the two games.

Concurrent Development

Under concurrent development, firms are formulating their development strategies simultaneously at time $t = 0$. As the choice of expenditure profile $c_i(t)$ has a one-to-one mapping to development times, this is equivalent to a simultaneous choice of development times.

The first order condition for firm i is $\partial\Pi_i^C/\partial T_i = -\frac{1}{r}\Delta_i e^{-rT_i} - \partial C(T_i;Z_i)/\partial T_i = 0$. Notice that once the order of completion is fixed (and hence the value of Δ_i determined), there are no remaining strategic interactions in the timing choices of the two firms. Moreover, with $\Delta_1 > \Delta_2$, firm 1 has greater incentive to compress its development process

[10] The payoff of the single firm is then simply $\Pi(T^*) = \frac{\pi_{00}}{r} + \frac{1}{r}\left(\sqrt{\Delta} - rZ\right)^2$. With two firms developing, the expression for payoffs is somewhat more complicated.

since it expects to be first to market in equilibrium. Firm 1's expectation that it will be first to complete is self-fulfilling as long as firm 2 does not have a sufficiently greater development capability, which is assured by assumption (A2).Assumption (A1) assures that equilibrium development times are finite and given by the solution to the two first order conditions. We have the following result.[11]

Proposition 4.2. *Under concurrent development, the equilibrium time-to-market for firm i is*

$$T_i^C = \frac{1}{r} \ln \left(1 - \frac{Z_i r}{\sqrt{\Delta_i}}\right)^{-1}. \tag{4.1}$$

The comparative statics are straightforward given that $Z_i = (1 - d_i)K$.

Corollary 4.3. *Under concurrent development, the equilibrium time-to-market of firm i is increasing in the complexity of the technology (K), the cost of capital (r) and decreasing in firm i's capability (d_i) and the increase in revenue flows to the ith firm to deploy the technology (Δ_i).*

Imitative Development

Let T_i^I be the time-to-market of firm i in the imitative development game. It is also be useful to define $\hat{T}_2^I$ as the amount of time that the follower spends on development. Thus the leader is developing the technology during the interval $[0, T_1^I]$ and the follower is developing during the interval $[T_1^I, T_2^I]$ where $T_2^I = T_1^I + \hat{T}_2^I$.

As this game has a sequential structure, we work backwards, first characterizing the optimal time spent on development for the follower and then solving for the leader's time-to-market. We can write the follower's payoff for any time T_1^I taken by firm 1 as $\Pi_2^I(T) = R_2(T_1^I, T_1^I + T) - e^{-rT_1^I} C(T; Z_2^I)$. Solving the first order condition $\partial \Pi_2^I / \partial T = 0$ yields the familiar expression $\hat{T}_2^I = \frac{1}{r} \ln \left(1 - Z_2^I r / \sqrt{\Delta_2}\right)^{-1}$.

Turning to the leader's problem, note that the follower's optimal time spent on development $\hat{T}_2^I$ is a constant independent of how long the leader takes. Hence, the leader's

[11] Of course there could also be an equilibrium where firm 2 is the leader and firm 1 is the follower. This occurs as long as an analogue of (A2) holds, namely $(1 - d_1)\sqrt{\Delta_1} > (1 - d_2)\sqrt{\Delta_2}$. However, by convention we are focusing on the case where firm 1 is the leader.

optimal development time maximizes $\Pi_1^I(T) = R_1(T, T+\hat{T}_2^I) - C(T; Z_1)$. Solving the first order condition $\partial \Pi_1^I / \partial T = 0$ yields $T_1^I = \frac{1}{r} \ln \left(1 - Z_1 r / \sqrt{\Delta_1^I}\right)^{-1}$ where

$$\Delta_1^I = \Delta_1 - (\pi_{10} - \pi_{11})(1 - Z_2^I r / \sqrt{\Delta_2}).$$

Note that $\Delta_1^I > \pi_{11} - \pi_{00}$ and hence (A3) assures that T_1^I is the unique, optimal development time for the leader. We collect these results in the following proposition.

Proposition 4.4. *In the imitative development game, the equilibrium time-to-market of the leader is*

$$T_1^I = \frac{1}{r} \ln \left(1 - \frac{Z_1 r}{\sqrt{\Delta_1^I}}\right)^{-1}.$$

The equilibrium time spent on development by the follower is

$$\hat{T}_2^I = \frac{1}{r} \ln \left(1 - \frac{Z_2^I r}{\sqrt{\Delta_2}}\right)^{-1} \tag{4.2}$$

and the time-to-market of the follower is $T_2^I = T_1^I + \hat{T}_2^I$.

We have the following comparative statics on the time spent on development by each firm using the fact that $Z_1 = (1 - d_1)K$ and $Z_2^I = (1 - s)(1 - d_2)K$.

Corollary 4.5. *Under imitative development, the equilibrium time spent on development for the follower,* $\hat{T}_2^I$*, is decreasing in* d_2*,* Δ_2 *and* s *and increasing in* r *and* K*. The equilibrium development time of the leader* T_1^I *is decreasing in* d_1 *and increasing in* K*,* d_2*,* r*, and* s*.*

5. Related Literature

With the model and equilibrium outcomes now fully specified, some readers may find it useful pause before turning to the main results in order to consider in more detail how our model relates to prior theoretical work on the acquisition of new technologies by competing firms. We limit our discussion to models where there is an explicit time dimension, in particular models of patent races, technology adoption, and the few prior studies of time-consuming technology development.

Time-to-market in patent race models is highly stochastic, usually with a constant hazard rate (for a survey of the patent race literature, see Langinier and Moschini 2002). This is consistent with the high level of uncertainty in research activities. In contrast, we study a deterministic relationship between effort and time-to-market, which we see as more relevant to the phenomenon of technology development. Another difference is that the patent race literature focuses on winner-take-all markets where the first firm to discover a new technology has enforceable property rights. In contrast both firms in our model are able to profit from bringing the new technology to market. In practice, "patents tend to be the least emphasized [mechanism to protect innovation] by firms in the majority of manufacturing industries, [whereas] secrecy and lead times tend to be emphasized most heavily" (Cohen et al., 2000: 2). Lead times in technology development and spillovers (the opposite of secrecy) are key features of our theory.

Now consider the relationship between our model of technology development and prior work on technology adoption. As noted in the introduction, our model is in many respects close to prior formal work on adoption of a new technology that is purchased from suppliers (see Hoppe, 2002, for a survey). Our revenue functions $R_i(T_1, T_2)$ are exactly those used by Reinganum (1981b) and Fudenberg and Tirole (1985) in their seminal models of technology adoption: Whether a given technology is internally developed or purchased from an external supplier need not matter for its effect on competition in product markets. On the cost side, the adoption literature is also based on a time-cost tradeoff and our cost function $C(T; Z_i)$ satisfies the general properties imposed by Fudenberg and Tirole (1985). With the same revenue function and the same time-cost tradeoff, our model specialized to the case of a single firm (as we do at the end of Section 4.2) is exactly the same as a single firm adoption problem in the received literature. It is with the introduction of competition that significant differences arise between adoption and development.

As the microprocessor industry illustrates, there can be two distinct scenarios when competing firms are developing a technology: concurrent and sequential development. In adoption models, there is simply no analogue to this distinction. The underlying reason is that adoption is taken as instantaneous rather than a time-consuming event (i.e., there is no lag between a firm's decision to adopt and the deployment of the technology in the market). Moreover, the instantaneous nature of adoption leaves no scope for knowledge spillovers or differing capabilities, which are central features of our model.

There is another important difference between adoption models and our model of technology development. Technology adoption with declining technology costs is a natural setting in which preemption dissipates rents (Fudenberg and Tirole, 1985). The possibilty of preemption pushes the time at which the technology leader adopts earlier and earlier until the costs are inflated to the point where the payoffs to the leader and follower are equalized (otherwise the follower could profitably deviate and adopt just before the leader). A prominent exception is Reinganum's (1981b) original model of technology diffusion, where she solves for a pre-commitment equilibrium that is analogous to our solution (T_1^C, T_2^C) of the concurrent development game. Reinganum (1989) justifies the use of pre-commitment equilibria by evoking the costs of a firm changing its technology strategy. However, the subsequent adoption literature has followed Fudenberg and Tirole (1985) and focused on preemptive behavior (Hoppe, 2002).

Competition is a less potent threat to rents when technologies are internally developed. In our imitative development game, the order of moves is taken as fixed and the leader's optimal development time is not affected by concerns of preemption. For our concurrent development game, Ruiz-Aliseda and Zemsky (2007) show that rent equalization does not occur despite the close parallels to adoption models. With adoption, if the leader delays its time-to-market, the follower is assumed to be able to instantaneously adopt the technology and preempt the leadership role. With development, the instantaneous acquisition of the technology that is required to support such rent equalization is prohibitively expensive. Moreover, Ruiz-Aliseda and Zemsky (2007) show that the original open loop equilibrium from Reinganum (1981b) can actually be subgame perfect. Two conditions are required. First, while completion is observable, a firm's cumulative effort is not. Second, the follower's incentive to develop the technology cannot be too much lower than the leader's.[12] The result arises precisely because development is a time-consuming activity while adoption has been modeled as an instantaneous activity. Although not required, any costs to adjusting a firm's planned expenditure profile $c_i(t, Z_i)$ along the lines suggested in Reinganum (1989) should only increase the range of parameters for which (T_1^C, T_2^C) is subgame perfect.[13]

[12] With symmetric capabilities ($d_1 = d_2$), the outcome (T_1^C, T_2^C) is supported as a subgame perfect equilibirum as long as $\Delta_1 < 6.85\Delta_2$, which is a fairly weak condition (Ruiz-Aliseda and Zemsly, 2007).

[13] Although Reinganum (1981b) is generally taken as a seminal paper on technology adoption, her analysis, which does not allow for pre-emptive behavior, actually fits better what we have called technology

There are a few prior papers on development timing. Katz and Shapiro (1987) is an important early step towards distinguishing development from adoption. In particular, they allow a follower firm to imitate a technology leader and benefit from spillovers. However, in other respects, their model retains important assumptions from the adoption literature, namely firms face a single, exogenously determined time-cost tradeoff and firms instantaneously deploy a technology once they decide to develop it. In contrast to our theory, there is then no distinction between concurrent and imitative development, no heterogeneity in firm capabilities, and preemption incentives still play an important role. In addition to Ruiz-Aliseda and Zemsky (2007), who study concurrent development, this paper also builds closely on Pacheco-de-Almeida and Zemsky (2007), who are the first to consider an imitative development game. The contibution of this paper is to characterize how competitve dynamics depend on whether development is imitative or concurrent. In addition, we generalize prior results to allow for heterogeneity in firm development capabilities.

6. The Effect of Imitation on Time-to-Market and Sustainability

The first major question we address is the effect of imitation, and the associated spillovers, on the speed with which a new technology diffuses into a given market. Technology diffusion is a classic topic in the innovation literature and was the original motivation for the model in Reinganum (1981b). In assessing the effect of imitation on technology diffusion, we are interested in how it influences both the leader's and the follower's time-to-market. For the leader, we get an unambiguous result.

Proposition 6.1. *The leader is faster to market under concurrent development than under imitative development; that is* $T_1^C < T_1^I$.

Under concurrent development, the time-to-market of the follower is fixed at T_2^C and is independent of the speed of the leader. Hence, the incentive for the leader to devote resources to accelerating its development process comes purely from reducing the lower bound on the interval of time $[T_1^C, T_2^C]$ over which the leader enjoys a competitive advantage from exclusive use of the technology. In contrast, under imitation the time-to-market

development. We see her paper as offering an early characterization of concurrent technology development. This is consistent with her discussion, especially in Reinganum (1989), of technology adjustment costs that are born over time.

of the follower falls with the time-to-market of the leader. This reduces the incentive for the leader to accelerate development since a faster time-to-market shifts forward but does not lengthen the period of advantage (i.e., decreases in T_1^I only shift the interval of advantage under imitation $[T_1^I, T_1^I + \hat{T}_2^I]$ earlier). Formally, the result arises from the fact that $\Delta_1 > \Delta_1^I$, with Δ_1 capturing the leader's return to accelerating development under the concurrent scenario and Δ_1^I capturing the leader's returns under the imitative scenario.

The effect of imitation and spillovers on the follower's time-to-market is more complicated. A key driver of the follower's time-to-market is the time it spends on development. Under both imitative and concurrent development, the returns to the follower from deploying the new technology are Δ_2. For $s > 0$, however, the development problem is easier under imitation (i.e., $Z_2^I < Z_2$). Hence, we have the following result.

Lemma 6.2. *If $s > 0$, the follower spends more time on development under concurrent than under imitative development, $\hat{T}_2^I < T_2^C$, while if $s = 0$ then $\hat{T}_2^I = T_2^C$.*

The unambiguous result in Lemma 6.2 does not translate into an unambiguous result on the follower's total time to market, which also varies with the leader's time to market. The possible non-monotonicities in the net effect is illustrated by considering an example, which we use repeatedly in the paper.

Example 6.3. *The parameters governing technology development are $d_1 = d_2 = 1/2$ and $K = 19$. The revenue flows are $\{\pi_{10}, \pi_{11}, \pi_{00}, \pi_{01}\} = \{4, 3, 2, 1.9\}$. The cost of capital is $r = 0.1$.*

Figure 6.1 shows the time-to-market for the leader and the follower as a function of spillovers for Example 6.3. Dashed lines give time-to-market under concurrent development, while the solid lines show time-to-market under imitation. As established in Proposition 6.1, the leader's time-to-market is always lower for concurrent development than for imitative development ($T_1^C < T_1^I$). The greater the level of spillovers, the longer the leader takes to bring the new technology to market with imitation.

Interestingly, for sufficiently small spillovers (i.e., s close to 0), the follower is faster to market with concurrent development. This is because imitation delays the start of the follower's development process and, as spillovers go to zero, the follower is spending as much time on development whether its approach is imitative or concurrent. We show

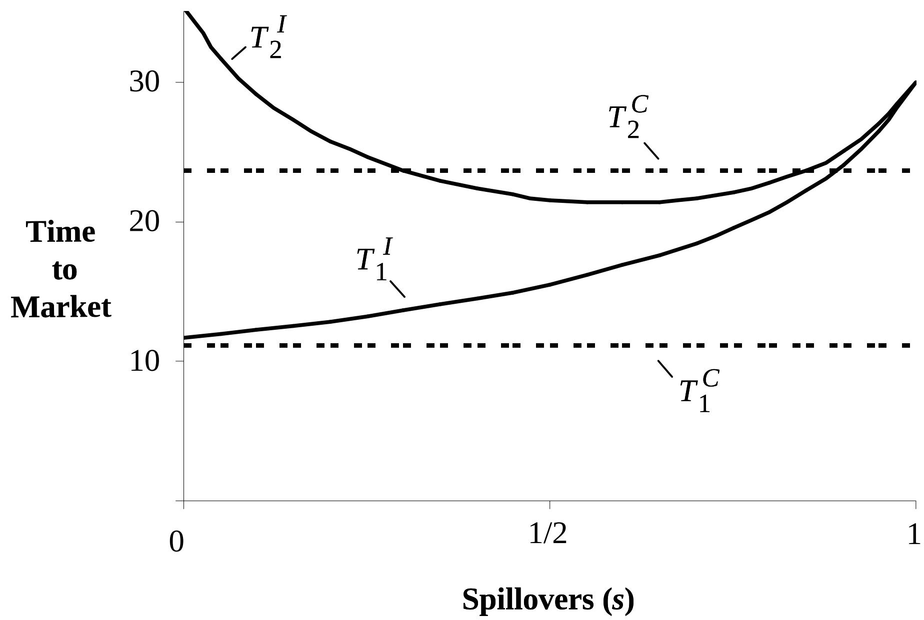

Figure 6.1: The time-to-market of leader and follower under imitative and concurrent development for Example 6.3.

below that this is a general result. Thus, for small spillovers imitation unambiguously leads to slower diffusion of the technology with both $T_1^C < T_1^I$ and $T_2^C < T_2^I$.

As spillovers increase, the follower's time spent on development with imitation, which is given by the gap between T_2^I and T_1^I, falls. However, the follower's start time T_1^I increases as the leader gets demotivated by the more rapid imitation. In the example, the net effect of increases in spillovers is suffiently negative for low values of s that there is a reversal: the follower is faster to market under imitation than under concurrent development. Although this need not happen in general, it does establish that there is no general ranking of T_2^C and T_2^I.

What happens to the follower's time-to-market as spillovers become large? In the example, there is a non-monotonicity and for sufficiently high spillovers the follower is, somewhat surprisingly, again faster to market with a concurrent strategy. As spillovers increase towards the upper limit of 1, the follower's development problem becomes trivial (i.e., $Z_2^I \to 0$) so that its time-to-market is just the leader's development time. The effect of imitation then comes down to whether the follower develops faster under concurrent development than the leader develops under imitative development.[14]

We collect the general results on when the follower is faster to market under concurrent development in part (i) of the following proposition. Part (ii) identifies conditions under which the follower is faster to market when imitating.

Proposition 6.4. *(i) The follower is faster to market under concurrent development, $T_2^C < T_2^I$, if either s is sufficiently close to 0 or if s is sufficiently close to 1 when $d_1 \leq d_2$ and $\pi_{00} > \pi_{01}$. (ii) For $s > 0$, the follower is faster to market under imitative development, $T_2^I < T_2^C$, if either d_1 is sufficiently close to 1 or if $\sqrt{\Delta_2} - rZ_2$ goes to zero (as long as $\sqrt{\Delta_1^I} - Z_1 r$ does not go to zero as well).*

Intuitively, the follower is faster to market with imitation when its development problem is much more challenging than is the leader's development problem. Then, the main effect of imitation is to reduce the follower's development time as demotivation of the leader is relatively less important. As $d_1 \to 1$, the leader's development problem becomes trivial. Conversely, as Z_2 gets close to $\sqrt{\Delta_2}/r$, the follower's development time under concurrent development goes to infinity because development of the new technology (as a follower without any spillovers) is approaching the point at which it is not economical. As long as the leader is not similarly demotivated in this limit, the follower will be faster to market under imitation.

6.1. Imitation and Sustainable Competitive Advantage

A central concern in business strategy is the sustainability of competitive advantage (Porter, 1985; Besanko et al. 2004). One can define competitive advantage as an asymmetry among competing firms that allows one firm to outcompete another firm in product markets. Our model is well suited to studying this phenomenon. Our firms are asymmetric in their product market positions precisely when one firm has developed the new technology and the other has not. Thus, we say that the leader in our model has a competitive advantage at a point in time when it has developed the new technology but the

[14] We have that $T_2^C < T_1^I$ *iff* $Z_2/\sqrt{\Delta_2} < Z_1/\sqrt{\Delta_1^I}$ and the ranking of time-to-market depends on the incentives to accelerate development relative to capabilities. We have that $\lim_{s\to 1} \Delta_1^I = \pi_{11} - \pi_{00}$, which is greater than $\sqrt{\Delta_2} = \sqrt{\pi_{11} - \pi_{01}}$ if $\pi_{00} > \pi_{01}$. Then $T_2^C < T_1^I$ in the limit as $s \to 1$ as long as Z_2 is not too much bigger than Z_1 (or equivalently d_2 not too much smaller than d_1). In the example we have $d_1 = d_2$ and $\pi_{00} > \pi_{01}$. Hence, for s sufficiently large we have that the follower is faster to market under concurrent development.

follower has not. One can define sustainability as the extent to which the technology asymmetry persists over time. In our model, sustainability is then precisely the difference in the time-to-market of the two firms, $T_2 - T_1$.

With both imitation and concurrent development, the firms have different time-to-market and hence in both cases there is a leader that enjoys a period of competitive advantage. What is the effect of imitation on the sustainability of the leader's competitive advantage? We find that there is no clear ranking, with the level of spillovers being a key moderating variable.

Proposition 6.5. *There exists an $\bar{s} \in (0,1)$ such that the leader's competitive advantage is more sustainable under imitation (i.e., $T_2^C - T_1^C < T_2^I - T_1^I$) if and only if $s < \bar{s}$.*

As spillovers become large, the effort required to develop the technology under imitation becomes small so that so that the leader's competitive advantage is more sustainable when the follower uses a strategy of concurrent development.[15] In contrast, for small s the main effect of imitation is only to delay the start of the follower's development activities and hence sustainability is greater when the follower is imitating.

Although the business strategy literature often treats sustainable competitive advantage as an end in itself, presumably the concept is of interest to the extent to which it is correlated with superior financial performance. It is straightforward to explore the links between technology-based advantages and performance in our model because there are closed-form expressions not only for each firm's time-to-market, but also for their profits.

7. Spillovers and Firm Profits

We now characterize the effect of imitation and spillovers on the profits of technology leaders and followers. We first consider the relative performance of the leader and the follower. If the follower is more capable than the leader (i.e., $d_2 > d_1$) then this alone could drive superior performance by the follower. Thus, we focus on the case where the leader is at least as capable as the follower.

Proposition 7.1. *Suppose that $d_1 \geq d_2$. (i) Under concurrent development, the leader always has a higher payoff than the follower. (ii) Under imitative development, the leader*

[15] Note that it is assumption (A3) which assures that the leader wants to develop the technology even in the limit as $s \to 1$.

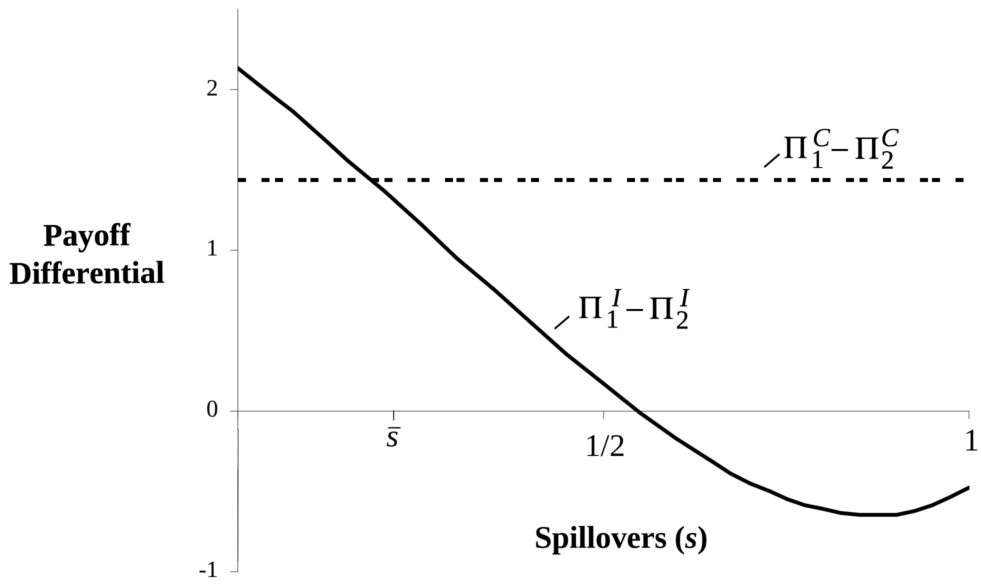

Figure 7.1: The difference between the leader's payoff and the follower's payoff under imitative and concurrent development for Example 6.3.

has a higher payoff if and only if spillovers are not too great: there exists an $\hat{s} \in (0, 1)$ *such that* $\Pi_1^I - \Pi_2^I > 0$ *iff* $s < \hat{s}$.

Figure 7.1 illustrates the results for Example 6.3. For concurrent development, the leader's competitive advantage unambiguously leads to superior performance (as long as there are not offsetting capability differences): $\Pi_1^C > \Pi_2^C$. The argument is as follows. Were the leader to deviate and develop at the same time as the follower then it would have the same profits for $d_1 = d_2$ and even higher profits for $d_1 > d_2$. The decision to use an earlier development time must raise the leader's profit, while the payoff of the follower is weakly decreasing as the leader develops earlier.

In contrast, for imitative development, the leader's period of competitive advantage need not lead to superior performance. In particular, as spillovers become large, the follower acquires the technology almost immediately after the leader and at a fraction of the development cost. Hence, the follower may well have a higher payoff. Thus, there is only a clear link between the leader's period of competitive advantage and superior performance in the case of concurrent development.

We now consider how each firm's absolute profit level is affected by whether development is concurrent or imitative. We start with the leader.

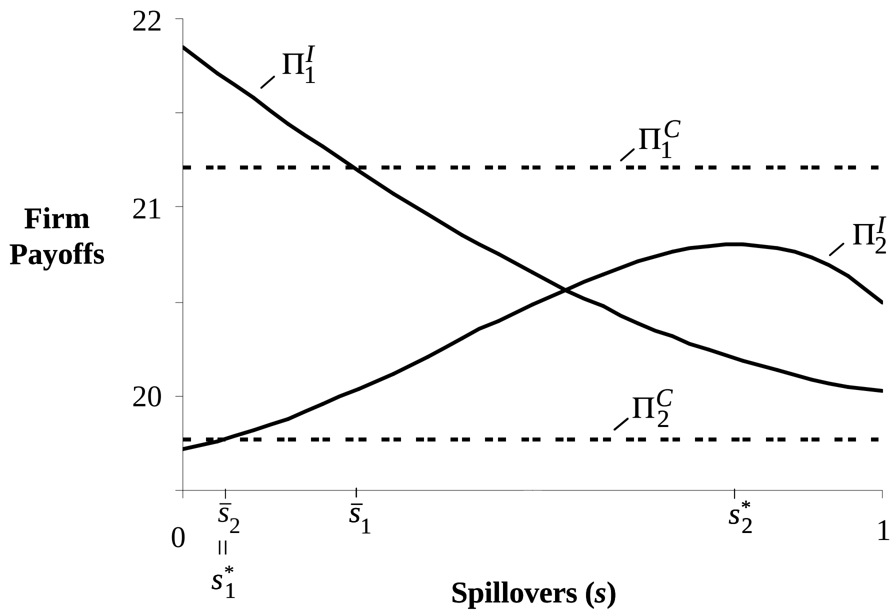

Figure 7.2: The payoff to the leader and the follower under imitative and concurrent development for Example 6.3.

Proposition 7.2. *There exists a critical level of spillovers* $\bar{s}_1 \in (0, 1)$ *such that the leader prefers that the follower uses an imitative strategy if and only if* $s < \bar{s}_1$.

The leader prefers imitation as long as spillovers are sufficiently small. On the one hand, imitative development has the advantage that delays to the leader's development also delay the follower (Proposition 6.1). On the other hand, for large spillovers sustainability is reduced by imitation (Proposition 6.5). Figure 7.2, which show the profits of each firm for Example 6.3, illustrates how the leader's profits under imitation Π_1^I fall below those under concurrent Π_1^C beyond the critical level of spillovers $\bar{s}_1$.

Consider the implications of Proposition 7.2 for the strategy of Intel. Once Intel had reduced the spillovers to AMD by ending its cross licensing agreement, the proposition suggests that Intel would benefit from shifting AMD from the concurrent development strategy it was then pursuing back to an imitative strategy. In fact, Intel did seek to force AMD back to an imitative strategy by changing the interfaces for its microprocessors so that AMD could not develop compatible designs until after Intel had released its chips to the market (Shih and Ofek, 2007).

What about AMD's behavior? Is their decision to shift to a concurrent development strategy in response to the fall in spillovers consistent with our theory?

Proposition 7.3. *(i) There exists a critical level of spillovers* $\bar{s}_2 \in [0, 1)$ *such that the follower prefers imitative development unless* $s < \bar{s}_2$. *(ii) In the new market case* $\bar{s}_2 > 0$. *More generally,* $\bar{s}_2 > 0$ *if either* $\sqrt{\Delta_2} > rZ_2(\sqrt{5} + 3)/2$ *or* π_{00} *sufficiently close to* π_{01}.

We find that for sufficiently high spillovers, the follower prefers imitation. In Figure 7.2 the follower prefers imitation for $s > \bar{s}_2 \cong 0.058$.[16] Figure 7.2 establishes that the follower's profits with imitation are potentially non-monotonic in s due to the demotivation of the leader. We consider this further in Subsection 7.1. At this point we simply note that the proof of Proposition 7.3 establishes that Π_2^I crosses Π_2^C at most once and only from below so that the critical value $\bar{s}_2$ is well defined.

7.1. Endogenous Spillovers

We now extend the scope of our analysis. Up until this point we have focused on firms' choice of time-to-market and the impact on firm profits. We now consider other firm decisions, especially those effecting the level of spillovers. A standard intuition is that spillovers are bad for the leader and hence it should consider a variety of actions to decrease them (Cassiman and Veugelers, 2002). The leader could, for example, seek to reduce the outflow of knowledge about technology development by locating its facilities far from competitors, by taking actions to reduce the turnover of key employees, and by having exclusive contracts with suppliers (to keep information from leaking to competitors via common suppliers). Conversely, spillovers are generally taken to be beneficial to followers who are seeking to imitate and hence they should consider a variety of actions to increase them. The follower could, for example, increase spillovers by building capabilities in reverse engineering, by collocating its facilities with the leader's, and by more closely aligning its strategy and organization with that of the leader so as to facilitate inter-organizational learning. What does our model say about the optimal levels of spillovers for technology leaders and followers?

[16] Interestingly, it is possible that $\bar{s}_2 = 0$ so that the follower prefers imitation for *all* levels of spillovers. Even without spillovers, the follower has a benefit from imitation, namely that the leader slows down which delays the onset of the follower's competitive disadvantage (although this does not arise in the new market case).

Proposition 7.4. *Suppose there is imitative development. (i) The profits of the leader are maximized for $s = 0$. (ii) The profits of the follower are optimized for a level of spillovers $s_2^* < 1$ if*

$$Z_1 r > \sqrt{\pi_{11} - \pi_{00}} \left(\frac{4}{3 + \frac{\pi_{10} - \pi_{01}}{\pi_{11} - \pi_{01}}} \right). \tag{7.1}$$

We find that spillovers are indeed bad for the leader under imitative development. This is because spillovers reduce the sustainability of the leader's competitive advantage.[17] In contrast, it is possible for spillovers to be too much of a good thing for the follower: for some parameter values (such as those in Example 6.3) the follower would not want to push spillovers all the way to one. The greater the spillovers, the faster the leader expects to be imitated and the less its incentives to compress its development process. Since the follower only starts its development once the leader is finished, the total time-to-market for the follower can potentially increase in spillovers (even as the follower's own development process is unambiguously getting shorter). Not only may the follower's time-to-market be lengthening, but even factoring in the cost savings from higher spillovers, we have shown that the follower's profits are potentially falling.[18]

We now turn to what we consider to be an even more surprising result. Is there really no downside to a technology leader that seeks to minimize spillovers? Consider Figure 7.2. As spillovers fall, the follower's profits under imitation fall to the point where it prefers concurrent development. Thus, if the follower can choose its development strategy based on the level of spillovers, then reducing spillovers to zero in the example will trigger a switch to a concurrent development strategy. Because the leader prefers that the follower imitates, this introduces a downside to reduced spillovers. Hence, it is possible that the leader's profits are optimized by allowing the follower enough spillovers that it is willing to engage in imitative development.

Let s_1^* be the optimal level of spillovers for the leader when the follower can choose between concurrent and imitative development.[19] In Figure 7.2, $s_1^* = \bar{s}_2 > 0$ gives this

[17] Pacheco-de-Almeida and Zemsky (2007) show this result for the case of $d_1 = d_2$.

[18] Because $\sqrt{\pi_{11} - \pi_{00}} > Z_1 r$ by (A3), for condition (7.1) to hold, it must be that π_{10} is large relative to π_{11}. The difference $\pi_{10} - \pi_{11}$ determines the extent to which the leader is demotivated by speedy imitation.

[19] There are different ways to model the endogeneity of both spillovers and the follower's development strategy. We are focusing on a particularly tractable approach, where the leader chooses spillovers and then the follower chooses its development strategy, as a way to establish the possibility that a leader can benefit

optimum. Although it is possible that $s_1^* > 0$, this need not be the case. First, it is possible that the follower prefers imitation for all levels of spillovers (Proposition 7.3) and second it must be the case that the leader still prefers imitation at the level of spillovers where the follower is willing to switch its strategy. We have the following possibility result.

Proposition 7.5. *Suppose that the model is extended so that the leader commits to a level of spillovers $s \in [0, 1)$ and then the follower commits to a concurrent or imitative development strategy. For any parameter values r, $d_1 \leq d_2$ and $\pi_{11} > \pi_{00}$, there exist revenue flows π_{01} and π_{10} such that the the optimal level of spillovers for the leader is $s_1^* = \bar{s}_2 > 0$.*

Our result strengthens the well-known possibility result in Gallini (1984) that a technology leader may want to license its technology to a competitor to keep it from engaging in its own R&D. We show that the leader may want to give up some of its intellectual property even without receiving any licensing payments in return.

8. The Incentive to Invest in Capabilities

Although the issue of firm capabilities and how they differ across firms is a central topic in management and strategy literatures, this phenomenon has received little attention in economics (Sutton, 2005). We offer a formalization of capabilities as determining the level of effort required to bring new technologies to market. Thus, the more capable a firm the faster it can develop a technology for a given cost level and the cheaper it can develop the technology for a given development time. We now consider the incentive of firms to invest in such capabilities, which helps to elucidate some of the drivers of capability differences across firms.

Definition 8.1. *Let firm i's* ***incentive to invest in capabilities*** *under concurrent ($\theta = C$) or imitative ($\theta = I$) development be $\partial\Pi_i^\theta/\partial d_i$. For $i, j \in \{1, 2\}$ and $\theta, \phi \in \{C, I\}$, we say that firm i's incentive to develop capabilities under θ development is greater than firm j's incentive under ϕ development if $\partial\Pi_i^\theta/\partial d_i > \partial\Pi_j^\phi/\partial d_j$ for all d_1 and d_2 that satisfy (A1)–(A3).*

by increasing spillovers. We assume that when the follower is indifferent between modes of development that it chooses imitation, as this makes results easier to state.

Suppose that the firms have an opportunity to make an incremental investment so as to increase their development capability. For example, they might be able to upgrade the project management software that they are using. If one firm has a greater incentive to invest in capabilities, then it will upgrade whenever its competitor does and for some upgrade costs it would upgrade while the competitor does not.[20]

With concurrent development, the incentives to invest in capabilities are quite straightforward:

$$\frac{\partial \Pi_i^C}{\partial d_i} = 2K\left(\sqrt{\Delta_i} - Z_i r\right) > 0 \text{ for } i = 1, 2. \tag{8.1}$$

The incentives are increasing in the impact of the technology on the firm's market position as given by Δ_i. Thus, the firm that expects to be the leader *ceteris paribus* has more incentives to invest in capabilities. Interestingly, a firm's incentive to invest in capabilities is increasing in its existing capability level. (This is because Z_i is falling in d_i). The increasing returns to capability development (i.e., $\frac{\partial^2 \Pi_i^C}{\partial d_i^2} > 0$) suggests that one could observe positive feedback where a leader's greater incentive to build capabilities can reinforce itself over time, although a formal result along these lines would depend on the nature of the costs of capability development.

Assumption (A2), which limits the extent to which the follower can have superior capabilities, is sufficient to assure that the leader has the greater incentive and we have the following result.

Proposition 8.2. *Under concurrent development: (i) The leader has greater incentive to invest in capability than the follower; and (ii) each firm's incentives to invest in capabilities is independent of the other firm's capabilities:* $\partial^2 \Pi_i^C / \partial d_1 \partial d_2 = 0$.

It is useful to note that the returns to capability development in (8.1) are non-monotonic in the complexity of the technology. The incentive to invest in capabilities goes to zero when either K becomes small, because development is easy, or when K is large (so that $\sqrt{\Delta_i} - Z_i r$ is small) as then the returns to development are pushed far into the future.

[20] For a discussion of capability development at Intel in response to increased competitive pressures, see the *Business Week* cover story "Inside Intel — It's Moving at Double-Time to Head Off Competitors" (June 1, 1992). In a discussion of Intel's investments in proprietary design tools, a company exeutive is quoted as saying "People have probably been wondering what we've been doing with those 386 profits. They've gone into 'enablers' that make it possible to design successive chips, each with two or three times as many transistors, at no increase in development time."

NOw consider the effect of imitation on the firm's incentive to invest in capabilities. We start with the leader's incentive, which is

$$\frac{\partial \Pi_1^I}{\partial d_1} = 2K\left(\sqrt{\Delta_1^I} - Z_1 r\right) > 0. \tag{8.2}$$

We then have the following result.

Proposition 8.3. *(i) Imitation reduces the leader's incentive to invest in capabilities. (ii) Under imitation, the more capable the follower, the lower is the leader's incentive to invest in capabilities:* $\partial^2 \Pi_1^I / \partial d_1 \partial d_2 < 0$.

Part (i) follows from the fact that the leader is in less of a hurry to develop under imitation due to $\Delta_1^I < \Delta_1$. Because the leader is less motivated to compress its development process, capabilities are less valuable. Thus, our model predcits that AMD's switch from imitiative to concurrent development would lead to increased investments in capabilities by Intel.

Part (ii) highlights a second contrast with concurrent development as now the follower's capability investment is a strategic substitute to the leader's investment. The more capable the follower, the less sustainable is the leader's technology advantage and the less it invests in speeding development; formally this follows from $\partial \Delta_1^I / \partial d_2 < 0$.

We turn now to the follower. A simple intuition is that imitation and having one's own development capabilities are substitutes, which would imply that imitation lowers the incentives of the follower to invest in capabilities. We find that this simple intuition is only partially correct. The incentives of the follower under imitation are considerably more comlex than the expressions (8.1) and (8.2). This is because the follower's incentives depend on when it expects to start its development, which is endogenously determined by the time-to-market of the leader, T_1^I, and this in turn varies with both the capalities of the follower and the level of spillovers. We can simplify the problem by considering the limit as $d_1 \to 1$ in which case the leader develops almost instantaneously regardless of the follower's capabilities or the level of spillovers. Even with this strong simplification, we do not find that imitation and capabilities are necessarily substitutes:

$$\lim_{d_1 \to 1} \frac{\partial \Pi_2^I}{\partial d_2} = 2\frac{Z_2^I}{1 - d_2}\left(\sqrt{\Delta_2} - Z_2^I r\right), \tag{8.3}$$

With $Z_2^I = (1-s)(1-d_2)K$, the RHS of (8.3) is the same as the RHS of (8.1) except that K is replaced by $(1-s)K$. That is, spillovers shift the level of K in the incentive expression for the follower, but we have already observed that the incentives to invest in capabilities are non-monotonic in K so that spillovers can either increase or decrease the incentives to invest in capabilities even in this simplified limit. Thus, it is possible that imitation increases rather than lowers a follower's incentives to invest in its capabilities.

Now consider whether the leader's capabilities increase or decrease the follower's incentives to develop its capabilities when imitating. A more capable leader has a faster time-to-market, which shifts forward the start of the follower's development process, which increases the returns to capability development. However, there is a potentially counter balancing effect in that the leader's development time becomes less responsive to influence by the speed of imitation and this reduces indirect incentives for capability development.

Lemma 8.4. *If $6\sqrt{\Delta_2} - 5rZ_2^I > (\pi_{11} - \pi_{00})/(rZ_2^I)$, then $\frac{\partial^2 \Pi_2^I}{\partial d_2 \partial d_1} > 0$. Otherwise, there exists a $\bar{\pi}_{10} > \pi_{11}$ such that $\frac{\partial^2 \Pi_2^I}{\partial d_2 \partial d_1} < 0$ if and only if $\pi_{10} > \bar{\pi}_{10}$.*

We find a positive effect of the leader's capabilities on the followers incentives unless two conditions hold. First, it must be that π_{11} is sufficiently greater than π_{00} (because Assumption (A1) implies that $6\sqrt{\Delta_2} - 5rZ_2^I > 0$), which assures that delays in the leader's development are sufficiently costly to the follower. Second, it must be that π_{10} is sufficiently large that there is a large demotivating effect on the leader of faster imitation.

When considering the incentives of the leader to develop capabilities we took as given the development strategy of the follower. What if the follower has the option to choose its development strategy? Then the leader's level of capabilities could potentially influence the follower's choice by shifting the relative profitability of imitation and concurrent development. Intuitively, one might expect that followers are less inclined to pursue concurrent development the more capable is the technology leader.

Proposition 8.5. *(i) In a new market, an increase in the development capability of the leader increases the relative payoff to the follower of imitation. (ii) More generally, an increase in the capability of the leader increases the relative payoff to the follower of imitation if π_{00} is sufficiently close to π_{01} while it decreases the relative payoff if π_{00} is sufficiently close to π_{11}.*

As the effect of the leader's deployment of the new technology on the follower's revenue flow becomes small (i.e., as $\pi_{00} \to \pi_{01}$), the follower's payoff (under both imitation and concurrent development) depends only on its own time-to-market. Because the leader's capabilities speed the follower's time-to-market under imitation and have no effect under concurrent development, the relative attractiveness of imitation is increasing in the leader's capabilities in this limit. This gives the result for the case of a new market, where $\pi_{00} = \pi_{01} = 0$.

As the effect of both firms deploying the technology becomes negligible (i.e., as $\pi_{00} \to \pi_{11}$), the follower cares only about minimizing the negative effect of its period of competitive disadvantage, rather than getting the technology in a timely way. Because the leader is less motivated to develop the technology under imitation, capabilities have a greater impact on its time-to-market in this case. As a result, the more capable the leader, the less likely the follower is to prefer imitation.

9. Conclusion

We seek to elaborate a theory of time-consuming technology development. Our main focus in this paper is the effects of imitative strategies and the associated spillovers on a variety of competitive outcomes including the speed with which new technologies difuse into an industry and the extent to which new technologies give rise to performance differences between technology leaders and followers. We address these novel issues while retaining many elements of prior work on technology adoption, which has the advantage of making it easier to identify the ways that technology competition differs depending on whether the technology is being purchased from external suppliers or being developed internally.

In terms of technology diffusion, we show that imitation always slows down the leader. There is no clear prediction for the follower: while spillovers always reduce the follower's time spent on development, they also demotivate the leader and hence the total time-to-market for the follower can increase or decrease with imitation. Under both concurrent and imitative development we have that there is a period of technology-based competitive advantage because firms differ in their time-to-market. Whether competitive advantage is more sustainable (i.e., lasts longer) under concurrent or imitative development depends on the degree of inter-firm spillovers. Competitve advantage is necessarily associated with superior performance under concurrent development, but not under imitation.

We show that the technology leader unambiguously wants low spillovers if the follower is committed to a strategy of imitation: lower spillovers make the leader's competitive advantage more sustainable. However, we show that the leader may want to allow some spillovers when the follower has a choice between concurrent and imitative development. Providing a minimal level of spillovers can then cause the follower to shift from concurrent to imitative development, which allows the leader to slow down its own development activities and, thereby, reduce its development costs. Conversely, the follower may actually benefit from reducing spillovers so as to increase the incentives of the leader to quickly develop the technology.

There are many ways to further develop a theory of time-consuming technology development. We use a very simple model of product market competition where the product market positions of firms are assumed to be symmetric except for the new technology. Clearly it would be desirable to consider asymmetries in product market positions that interact with the value of the technology to each of the firms as in Riordan (1992). Another important simplification is that the effect of the new technology on the revenue flows is assumed to be known, whereas there is often considerable uncertainty in this area which is only resolved once the leader brings the new technology to market. Adding the resolution of market uncertainty by the leader would introduce another avenue for spillovers from the leader to the follower.

We believe that there is a substntial opportunity to pursue emperical work on the timing of development project among competiting firms. Empirical work in this area should be facilitated by data on development times, project complexity and technology spillovers that is publicly available in many industries such as semiconductors, consumer electronics, oil and gas, and automobiles where major projects are often tracked in the industry trade press. Empirical proxies for inter-firm spillovers can be constructed from data on licensing and cross-licensing agreements for which there usually is news coverage. Pacheco-de-Almeida at al. (2007) make use of rich data on the development of new production facilities in the oil and gas industry to empirically study time-to-market and development capabilities. Our results suggests several other lines of investigation, including research that considers a firm's choice of concurrent versus imitative development based on the level of knowledge spillovers. An alternative emperical approach could be to make use of the data in the Carnegie Mellon Survey, which has items on imitation lags, complexity, and secrecy (Cohen et al., 2000). At a basic level, it would be useful to extend and update Mansfield's (1971, 1988) work by systematically collecting data on time-cost tradeoffs in the development of new technologies across firms and industries.

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10. Appendix

Proof of Proposition 4.1 Consider a firm that seek to develop a technology requiring total effort Z_i over the interval of time $[0, T]$. Let $Z_i(t) = \int_0^t \sqrt{c(\tau)}d\tau$ denote the cumulative effort taken by date t under expenditure profile $\{c(\tau)\}_{\tau\in[0,t]}$. Therefore, as the firm develops the new technology by date T, it solves the following program:

$$\min_{c(t)\geq 0} \int_0^T c(t)e^{-rt}dt$$

$$\text{s.t. } \frac{dZ_i(t)}{dt} = \sqrt{c(t)},\ Z_i(0) = 0,\ Z_i(T) = Z.$$

Denoting the costate variable by $\lambda(t)$, we can write the Hamiltonian function as $H(c) = -ce^{-rt} + \lambda(t)\sqrt{c}$. The necessary and sufficient conditions for an interior maximum require that the following conditions hold:

$$\frac{\lambda(t)}{2\sqrt{c}} = e^{-rt} \quad (10.1)$$

$$\frac{dZ_i(t)}{dt} = \sqrt{c} \quad (10.2)$$

$$\frac{d\lambda}{dt} = 0 \quad (10.3)$$

$$Z_i(0) = 0,\ Z_i(T) = Z_i \quad (10.4)$$

Using (10.3), we have that $\lambda(t) = \lambda$ for some constant λ, so $c(t) = \left(\frac{\lambda e^{rt}}{2}\right)^2$ by (10.1). This, together with (10.2), implies that $Z_i(T) - Z_i(0) = \frac{\lambda(e^{rT}-1)}{2r}$. Hence, (10.4) implies that $\lambda = \frac{2rk}{e^{rT}-1}$, and thus we have that the cost minimizing expenditure profile $c^*(t; T, Z_i)$ and the time-cost tradeoff $C(T; Z_i)$ are as stated in the lemma. ■

Proof of Proposition 4.2 The first order condition for firm i in concurrent development is $\partial\Pi_i^C/\partial T_i = \Delta_i e^{-rT_i} - Z_i^2 r^2 \frac{e^{T_i r}}{(e^{T_i r}-1)^2} = 0$. Substituting $T_i = \frac{\ln x}{r}$ where $x > 1$ solves for a unique T_i^C in (4.1). ■

Proof of Corollary 4.3 The comparative statics of T_i^C w.r.t K, d_i, and Δ_i follow by inspection. As for the comparative w.r.t. r, we know that $\frac{\partial e^{-rT_i^C}}{\partial r} = (-r)e^{-rT_i^C}\frac{\partial T_i^C}{\partial r} \Leftrightarrow \frac{\partial T_i^C}{\partial r} = (-\frac{1}{r})e^{rT_i^C}\frac{\partial e^{-rT_i^C}}{\partial r}$ and $\frac{\partial e^{-rT_i^C}}{\partial r} = -\frac{Z_i}{\sqrt{\Delta}} < 0$, which establishes that $\frac{\partial T_i^C}{\partial r} > 0$. ■

Proof of Proposition 4.4 The result follows by noting that the first order condition for the optimal time of the follower in imitative development is identical to that in concurrent development (see proof of Proposition 4.2), except that the total effort for the follower is now $Z_2^I = (1-s)(1-d_2)K$ rather than $Z_2 = (1-d_2)K$. ■

Proof of Corollary 4.5 The comparative statics of $\hat{T}_2^I$ w.r.t K, d_2, Δ_2, and r are analogous to those of T_2^C in the proof of corollary (4.3), whereas the effect of s on $\hat{T}_2^I$ follows by inspection. The comparative statics of T_1^I w.r.t. d_1, d_2, and s also follows by inspection. To establish that T_1^I is increasing in K, note that (**??**) can be rewritten as $T_1^I = \frac{1}{r}\ln\left(1 - \frac{(1-d_1)r}{\sqrt{\Delta_1^I/K^2}}\right)^{-1}$ and $\partial\left(\Delta_1^I/K^2\right)/\partial K = -\frac{1}{K^3}\left(\Delta_1^I + \pi_{11} - \pi_{00}\right) < 0$. To establish that T_1^I is increasing in r, it is sufficient to show that (**??**) can be rewritten as $T_1^I = \frac{1}{r}\ln\left(1 - \frac{(1-d_1)K}{\sqrt{\Delta_1^I/r^2}}\right)^{-1}$ and $\partial\left(\Delta_1^I/r^2\right)/\partial r = -\frac{1}{r^3}\left(\Delta_1^I + \pi_{11} - \pi_{00}\right) < 0$. ■

Proof of Proposition 6.1 Follows by inspection since $\Delta_1 > \Delta_1^I$. ■

Proof of Proposition 6.2 Follows by inspection since $Z_2^I < Z_2$. ■

Proof of Proposition 6.4 We can rewrite $T_2^C < T_2^I$ as

$$s < \left(\frac{1-d_1}{1-d_2}\right)\left(\frac{\sqrt{\Delta_2} - (1-d_2)\,Kr}{\sqrt{\Delta_1^I} - (1-d_1)\,Kr}\right). \tag{10.5}$$

(i) By Assumptions (A1) and (A3), The RHS of (10.5) is positive for all s and hence it is satisfied for s sufficiently close to 0. Suppose that $d_1 = d_2$. In the limit as $s \to 1$, we then have that (10.5) becomes $\sqrt{\Delta_1^I} = \sqrt{\pi_{11} - \pi_{00}} < \sqrt{\Delta_2}$, which is satisfied *iff* $\pi_{00} > \pi_{01}$. Because the RHS of (10.5) is decreasing in d_1, we have that this result generalizes to $d_1 \le d_2$.

(ii) Holding fixed the other parameters, in the limit as $d_1 \to 1$ we have that the RHS of (10.5) goes to zero. Hence, the condition is not satisfied in the limit for $s > 0$. In the limit as Z_2 goes to $\sqrt{\Delta_2}/r$ the RHS of (10.5) goes to zero as long as $\sqrt{\Delta_1^I} - Z_1 r$ does not go to zero as well. ■

Proof of Proposition 6.5 The condition $T_2^I - T_1^I > T_2^C - T_1^C$ is equivalent to $s < \bar{s}$ where

$$\bar{s} \equiv \frac{Z_1}{Z_2}\frac{\sqrt{\Delta_2} - Z_2 r}{\sqrt{\Delta_1} - Z_1 r}.$$

From (A1) and $Z_i > 0$, we have that $\bar{s} > 0$. We can rewrite (A3) as $\bar{s} < 1$ (an intermediate step is to rewrite (A3) as $\sqrt{\Delta_1}/Z_2 - r > \sqrt{\Delta_2}/Z_2 - r$). This establishes the existence of an $\bar{s} \in (0,1)$ such that sustainability is greater under imitation if and only if $s < \bar{s}$. ■

Proof of Proposition 7.1 (i) Assume concurrent development. We have that $\Pi_1^C\left(T_2^C, T_2^C\right) \ge \Pi_2^C\left(T_2^C, T_2^C\right)$, since $R_1(T_2^C, T_2^C) = R_2(T_2^C, T_2^C)$ and $C(T_2^C; Z_1) \le C(T_2^C; Z_2)$ with $d_1 \ge d_2$. Also, $\Pi_2^C\left(T_2^C, T_2^C\right) \ge \Pi_2^C\left(T_1^C, T_2^C\right)$ because $R_2(T_2^C, T_2^C) \ge R_2(T_1^C, T_2^C)$ since $\pi_{00} \ge \pi_{01}$. Finally, $\Pi_1^C\left(T_1^C, T_2^C\right) > \Pi_1^C\left(T_2^C, T_2^C\right)$ because the leader is optimizing at T_1^C, $T_1^C < T_2^C$, and this optimum is unique. Hence, $\Pi_1^C\left(T_1^C, T_2^C\right) > \Pi_2^C\left(T_1^C, T_2^C\right)$. (ii) Assume imitative development. Note that $1 - e^{-r\hat{T}_2^I} = \frac{Z_2^I r}{\sqrt{\Delta_2}}$. The difference in revenues between the leader and the follower is

$$\begin{aligned} R_1(T_1^I, T_2^I) - R_2(T_1^I, T_2^I) &= \int_{T_1^I}^{T_2^I} (\pi_{10} - \pi_{01})\, e^{-rt} dt = \frac{1}{r}(\pi_{10} - \pi_{01})\, e^{-rT_1^I}\left(1 - e^{-r\hat{T}_2^I}\right) \\ &= e^{-rT_1^I}(\pi_{10} - \pi_{01})\frac{Z_2^I}{\sqrt{\Delta_2}}. \end{aligned}$$

Since $C(T_1^I; Z_1) = Z_1 \left(\sqrt{\Delta_1^I} - Z_1 r\right)$ and $e^{rT_1^I} = \sqrt{\Delta_1^I} / \left(\sqrt{\Delta_1^I} - Z_1 r\right)$, we have that $C(T_1^I; Z_1) e^{rT_1^I} = Z_1 \sqrt{\Delta_1^I}$. In addition, $C(\hat{T}_2^I; Z_2^I) = Z_2^I \left(\sqrt{\Delta_2} - Z_2^I r\right)$. The difference in costs (discounted to $t = 0$) is then

$$\begin{aligned} C(T_1^I; Z_1) - C(\hat{T}_2^I; Z_2^I) e^{-rT_1^I} &= e^{-rT_1^I} \left(C(T_1^I; Z_1) e^{rT_1^I} - C(\hat{T}_2^I; Z_2^I) \right) \\ &= e^{-rT_1^I} \left(Z_1 \sqrt{\Delta_1^I} - Z_2^I \sqrt{\Delta_2} + \left(Z_2^I\right)^2 r \right). \end{aligned}$$

The difference in profits is then $\Pi_1^I - \Pi_2^I = R_1(T_1^I, T_2^I) - R_2(T_1^I, T_2^I) - C(T_1^I; Z_1) + C(\hat{T}_2^I; Z_2^I) e^{-rT_1^I} = e^{-rT_1^I} Z_2^I W$, where $W = \left(\frac{\pi_{10} - \pi_{01}}{\sqrt{\Delta_2}} + \sqrt{\Delta_2} - r Z_2^I - \frac{Z_1}{Z_2^I} \sqrt{\Delta_1^I} \right)$. Then, $\Pi_1^I > \Pi_2^I$ *iff* $W > 0$.

To establish the existence of an $\hat{s}$ such that $\Pi_1^I > \Pi_2^I$ *iff* $s < \hat{s}$, we show that $W > 0$ for $s = 0$, $\lim_{s \to 1} W < 0$, and that $\partial^2 W / \partial s^2 < 0$ so that W has only one zero in the interval $(0, 1)$. By inspection, $\lim_{s \to 1} W < 0$. Conversely, for $s = 0$ we have

$$\lim_{s \to 0} W = \frac{1}{\sqrt{\Delta_2}} \left(\pi_{10} - \pi_{01} + \sqrt{\Delta_2} \left(\sqrt{\Delta_2} - r(1 - d_2) K \right) - \frac{(1 - d_1)}{(1 - d_2)} \sqrt{\Delta_1^I \Delta_2} \right) > 0,$$

where the inequality follows from $\pi_{10} - \pi_{01} > \max\{\Delta_1^I, \Delta_2\}$ and $d_1 \geq d_2$, and from assumption (A1) $\sqrt{\Delta_2} > r Z_2$. Finally, we have that

$$\frac{\partial W}{\partial s} = K r \left(1 - d_2\right) - \frac{1 - d_1}{\left(1 - d_2\right) \left(1 - s\right) \sqrt{\Delta_1^I}} \left(\frac{\Delta_1^I}{1 - s} - \frac{(\pi_{10} - \pi_{11})(1 - d_2) K r}{2 \sqrt{\Delta_2}} \right),$$

which is of the general form $\partial W / \partial s = A - B(s) \left(C(s) - D\right)$ with A and D constant in s. Thus, $\partial^2 W / \partial s^2 = -\left(B(s)' \left(C(s) - D\right) + B(s) C(s)'\right)$, where $B(s) > 0$ and $B(s)' > 0$ by inspection, $C(s)' = \frac{\pi_{11} - \pi_{00}}{(1 - s)^2} > 0$, and $C(s) - D = \frac{1}{1 - s} \left(\pi_{11} - \pi_{00} + \frac{(\pi_{10} - \pi_{11})(1 - s)(1 - d_2) K r}{2 \sqrt{\Delta_2}} \right) > 0$. Hence, $\partial^2 W / \partial s^2 < 0$ and there exists a unique $\hat{s}$ such that the profits of the leader are higher than the follower *iff* $s < \hat{s}$. ■

Proof of Proposition 7.2 This proof has three parts. (i) We first show that $\Pi_1^I(s)$ is strictly decreasing in s. If $s_0 > s_1$, then $\Pi_1^I \left(T_1^I\big|_{s_0}, T_1^I\big|_{s_0} + \hat{T}_2^I\Big|_{s_0}, s_0 \right) < \Pi_1^I \left(T_1^I\big|_{s_0}, T_1^I\big|_{s_0} + \hat{T}_2^I\Big|_{s_1}, s_1 \right)$ where $T_1^I\big|_{s_0}$ and $\hat{T}_2^I\Big|_{s_0}$ are the optimal development times for s_0 and $\hat{T}_2^I\Big|_{s_1}$ is the optimal development time for s_1. This is because the optimal development time for the follower is decreasing in s. Also, we have that $\Pi_1^I \left(T_1^I\big|_{s_0}, T_1^I\big|_{s_0} + \hat{T}_2^I\Big|_{s_1}, s_1 \right) < \Pi_1^I \left(T_1^I\big|_{s_1}, T_1^I\big|_{s_1} + \hat{T}_2^I\Big|_{s_1}, s_1 \right)$ because the leader is optimizing for s_1. This establishes the result. (ii) We have that $\Pi_1^I(s = 0) > \Pi_1^C$ because $\hat{T}_2^I(s = 0) = T_2^C$ but in imitation the follower only starts developing once the leader has completed its development process. So, even if $T_1^I = T_1^C$, the leader will be better off in imitation than in concurrent. Optimizing on T_1^I further increases the profits of imitation relative to concurrent development for the leader. (iii) Finally, $\lim_{s \to 1^-} \Pi_1^I(s) - \Pi_1^C = 2 \left(1 - d_1\right) K \left(\sqrt{\pi_{10} - \pi_{00}} - \sqrt{\pi_{11} - \pi_{00}} \right) -$

$\frac{(1-d_2)K}{\sqrt{\pi_{11}-\pi_{01}}}(\pi_{10}-\pi_{11})$, which is monotonically decreasing in π_{10} and equal to zero when $\pi_{10}\to\pi_{11}^{+}$. Hence, since $\pi_{10}>\pi_{11}$ by assumption, we have that $\lim_{s\to 1^-}\Pi_1^I(s)-\Pi_1^C<0$. This establishes that there is a unique critical level of spillovers $\bar{s}_1\in(0,1)$ such that the leader prefers imitative development if and only if $s<\bar{s}_1$. ■

Proof of Proposition 7.3 (i) The profits of the follower in the imitation and concurrent cases are

$$\begin{aligned}
\Pi_2^I(s) &= \left(1-\frac{(1-d_1)Kr}{\sqrt{\Delta_1^I}}\right)\Bigg(\frac{\pi_{11}-\pi_{00}}{r}- \\
&\quad (1-d_2)K(1-s)\left(2\sqrt{\Delta_2}-r(1-s)(1-d_2)K\right)\Bigg)+\frac{\pi_{00}}{r}, \\
\Pi_2^C &= \frac{(1-d_1)K}{\sqrt{\Delta_1}}(\pi_{00}-\pi_{01})-(1-d_2)K\left(2\sqrt{\Delta_2}-(1-d_2)Kr\right)+\frac{\pi_{11}}{r},
\end{aligned}$$

where $\Delta_1^I=(\pi_{10}-\pi_{00})-(\pi_{10}-\pi_{11})(1-\frac{(1-s)(1-d_2)Kr}{\sqrt{\Delta_2}})$. First, assume that $\Pi_2^C>\Pi_2^I(s=0)$ (see point (ii) below for the conditions under which this assumption is satisfied). Second, we know that $\lim_{s\to 1^-}\Pi_2^I(s)>\Pi_2^C\big|_{\pi_{01}\to\pi_{00}^-}$ since $\hat{T}_2^I=0$, $C_2^I\left(\hat{T}_2^I\right)=0$, $\Delta_1^I=\pi_{11}-\pi_{00}=\Delta_2|_{\pi_{01}\to\pi_{00}^-}$, and thus $T_1^I=T_2^C\big|_{\pi_{01}\to\pi_{00}^-}$. Also, $\Pi_2^C\big|_{\pi_{01}\to\pi_{00}^-}>\Pi_2^C$ because $\frac{\partial\Pi_2^C}{\partial\pi_{01}}>0$. Thus, $\lim_{s\to 1^-}\Pi_2^I(s)>\Pi_2^C$. Finally, we also know that $\Pi_2^I(s)'''<0$ since $\Pi_2^I(s)''=G(s)''F(s)+2G(s)'F(s)'+G(s)F(s)''$ is decreasing in s, where $G(s)=\left(1-\frac{(1-d_1)Kr}{\sqrt{\Delta_1^I}}\right)$ and $F(s)=\left(\frac{\pi_{11}-\pi_{00}}{r}-(1-d_2)K(1-s)\left(2\sqrt{\Delta_2}-r(1-s)(1-d_2)K\right)\right)$. Note that the terms $G(s)''F(s)$ and $2G(s)'F(s)'$ become more negative in s, whereas $G(s)F(s)''$ is positive and decreasing in s. $\Pi_2^I(s)'''<0$ implies that $\Pi_2^I(s)$ can only be overall concave in s, overall convex in s, or convex for s small and then concave for s sufficiently large, which together with $\Pi_2^C>\Pi_2^I(s=0)$ and $\lim_{s\to 1^-}\Pi_2^I(s)>\Pi_2^C$ is enough to establish the uniqueness of a critical value $\bar{s}_2$ such that $\Pi_2^I(s)<\Pi_2^C$ if and only if $s<\bar{s}_2$.

(ii) Assume $s=0$. We have that $\pi_{00}\to\pi_{01}^{+}$, then $\Pi_2^I(s=0)<\Pi_2^C$ simplifies to $2-\frac{r(1-d_2)K}{\sqrt{\pi_{11}-\pi_{01}}}<\frac{\sqrt{\pi_{11}-\pi_{01}}}{r(1-d_2)K}$, which is always true since $\frac{\sqrt{\pi_{11}-\pi_{01}}}{r(1-d_2)K}>1$. When $\pi_{00}\to\pi_{11}^{-}$, then $\Pi_2^I(s=0)>\Pi_2^C$ simplifies to $\sqrt{\frac{(1-d_2)rK}{\sqrt{\pi_{11}-\pi_{01}}}}\left(2-\frac{r(1-d_2)K}{\sqrt{\pi_{11}-\pi_{01}}}\right)>1$, which is satisfied if and only if $\sqrt{\Delta_2}<\frac{\sqrt{5}+3}{2}r(1-d_2)K$. Also, $\frac{\partial\left(\Pi_2^I-\Pi_2^C\right)\big|_{s=0}}{\partial\pi_{00}}>0$ because $\sqrt{\Delta_1^I}+\frac{\pi_{00}-\pi_{01}}{2\sqrt{\Delta_1}}>\sqrt{\Delta_1^I}\sqrt{\frac{\Delta_1^I}{\Delta_1}}+\frac{\pi_{00}-\pi_{01}}{2\sqrt{\Delta_1}}\frac{\Delta_1^I}{\Delta_1}$. Thus, if $\sqrt{\Delta_2}>\frac{\sqrt{5}+3}{2}r(1-d_2)K$, it must be that the follower always prefers concurrent when $s=0$. Otherwise, if $\sqrt{\Delta_2}<\frac{\sqrt{5}+3}{2}r(1-d_2)K$, then $\lim_{\pi_{00}\to\pi_{11}^{+}}\left(\Pi_2^I(s=0)>\Pi_2^C\right)$ and $\lim_{\pi_{00}\to\pi_{01}^{+}}\left(\Pi_2^I(s=0)<\Pi_2^C\right)$, and since $\left(\Pi_2^I-\Pi_2^C\right)\big|_{s=0}$ is continuous and strictly increasing in π_{00}, there must be a unique critical value $\overline{\pi}_{00}\in(\pi_{01},\pi_{11})$ such that $\Pi_2^I(s=0)<\Pi_2^C$ if and only if $\pi_{00}\in[\pi_{01},\bar{\pi}_{00})$. From (i), we know that when $\Pi_2^I(s=0)<\Pi_2^C$, we have that $\bar{s}_2>0$. ■

$\sqrt{\Delta_2}>rZ_2(\sqrt{5}+3)/2$

Proof of Proposition 7.4 To establish that the optimal s for the follower is less than 1, it is sufficient to show that $\partial\Pi_2^I(s)/\partial s<0$ at $s=1$. The follower's profits in the imitative development scenario are

$$\Pi_2^I(s) = \left(\frac{1}{r} - \frac{(1-d_1)K}{\sqrt{\Delta_1^I}}\right)\left(\pi_{11} - 2\sqrt{\Delta_2}(1-s)(1-d_2)Kr + (1-d_2)^2 r^2 K^2 (1-s)^2\right) + \pi_{00}\frac{(1-d_1)K}{\sqrt{\Delta_1^I}}.$$

We then have that

$$\lim_{s\to 1}\frac{\partial \Pi_2^I(s)}{\partial s} = \frac{(1-d_2)K\left(4\sqrt{\pi_{11}-\pi_{00}}(\pi_{11}-\pi_{01}) - (1-d_1)Kr(\pi_{10}-4\pi_{01}+3\pi_{11})\right)}{2\sqrt{\pi_{11}-\pi_{00}}\sqrt{\pi_{11}-\pi_{01}}}$$

so that $\partial \Pi_2^I(s)/\partial s < 0$ at $s=1$ if and only if condition (7.1) holds. ■

Proof of Proposition 7.5 Suppose that $\sqrt{\Delta_2} > rZ_2(\sqrt{5}+3)/2$ or, alternatively, that $\sqrt{\Delta_2} < rZ_2(\sqrt{5}+3)/2$ but π_{00} is sufficiently close to π_{01}. Then, from proposition (7.3) we know that there exists a unique critical value $\bar{s}_2 \in (0,1)$ such that the follower prefers imitation if and only if $s > \bar{s}_2$. If π_{10} is sufficiently close to π_{11} (i.e., $\pi_{10} \to \pi_{11}^+$), then from proposition (7.2) we know that the leader prefers imitation for all $s \in [0,1)$ and, thus, $s_1^* = \bar{s}_2 > 0$. If π_{10} is not sufficiently close to π_{11} but $\bar{s}_2 < \bar{s}_1$, then we still have that $s_1^* = \bar{s}_2 > 0$. ■

Proof of Proposition 8.2 In concurrent development, the profit expressions are given by

$$\Pi_1^C = \frac{(1-d_2)K}{\sqrt{\Delta_2}}(\pi_{10}-\pi_{11}) - (1-d_1)K\left(2\sqrt{\Delta_1} - Z_1 r\right) + \frac{\pi_{11}}{r}$$

$$\Pi_2^C = \frac{(1-d_1)K}{\sqrt{\Delta_1}}(\pi_{00}-\pi_{01}) - (1-d_2)K\left(2\sqrt{\Delta_2} - Z_2 r\right) + \frac{\pi_{11}}{r}.$$

(i) The incentives to invest in capabilities are $\frac{\partial \Pi_i^C}{\partial d_i} = 2K\left(\sqrt{\Delta_i} - Z_i r\right) > 0$ for $i=1,2$ and, thus, $\frac{\partial \Pi_1^C}{\partial d_1} - \frac{\partial \Pi_2^C}{\partial d_2} = 2K\left(\sqrt{\Delta_1} - \sqrt{\Delta_2} + r(Z_2 - Z_1)\right) > 0$. (ii) $\partial^2 \Pi_i^C/\partial d_i \partial d_{-i} = 0, i=1,2$ by inspection. ■

Proof of Proposition 8.3 In imitative development, the profit expressions are

$$\Pi_1^I = \frac{\Delta_1^I}{r} - (1-d_1)K\left(2\sqrt{\Delta_1^I} - r(1-d_1)K\right) + \frac{\pi_{00}}{r} \tag{10.6}$$

$$\Pi_2^I = \left(1 - \frac{(1-d_1)Kr}{\sqrt{\Delta_1^I}}\right)\left(\frac{\pi_{11}-\pi_{00}}{r} - (1-d_2)K(1-s)\left(2\sqrt{\Delta_2} - r(1-s)(1-d_2)K\right)\right) + \frac{\pi_{00}}{r}. \tag{10.7}$$

(i) $\frac{\partial \Pi_1^I}{\partial d_1} = 2K\left(\sqrt{\Delta_1^I} - Z_1 r\right) < \frac{\partial \Pi_1^C}{\partial d_1} = 2K\left(\sqrt{\Delta_1} - Z_1 r\right)$. (ii) The cross derivative $\partial^2 \Pi_1^I/\partial d_1 \partial d_2 = -(\pi_{10}-\pi_{11})\frac{(1-s)K^2 r}{\sqrt{\Delta_1^I}\sqrt{\Delta_2}} < 0$. ■

Proof of Lemma 8.4 The follower's profits in imitative development are

$$\Pi_2^I = \left(1 - \frac{Z_1 r}{\sqrt{\Delta_1^I}}\right)\left(\frac{\pi_{11}-\pi_{00}}{r} - Z_2^I\left(2\sqrt{\Delta_2} - rZ_2^I\right)\right) + \frac{\pi_{00}}{r}$$

, where $\Delta_1^I = \Delta_1 - (\pi_{10} - \pi_{11})(1 - Z_2^I r/\sqrt{\Delta_2})$. The expression for the cross derivative is

$$\frac{\partial^2 \Pi_2^I}{\partial d_2 \partial d_1} = 2K(1-s)\frac{Kr}{\sqrt{\Delta_1^I}}\left(\sqrt{\Delta_2} - rZ_2^I - \frac{1}{4}\frac{\pi_{10}-\pi_{11}}{\Delta_1^I}\left(\frac{\pi_{11}-\pi_{00}}{\sqrt{\Delta_2}} - rZ_2^I\left(2 - \frac{rZ_2^I}{\sqrt{\Delta_2}}\right)\right)\right)$$

, which is of the form $\partial^2\Pi_2^I/\partial d_2\partial d_1 = \frac{A}{4(\delta\alpha+\gamma\beta)}(4\delta\alpha(\alpha-\beta) + \gamma(6\beta\alpha - 5\beta^2 - \delta)$ where $A = 2K(1-s)\left(\frac{Kr}{\sqrt{\Delta_1^I}}\right)$, $\alpha = \sqrt{\Delta_2}$, $\beta = rZ_2^I$, $\gamma = \pi_{10} - \pi_{11}$, and $\delta = \pi_{11} - \pi_{00}$. Since $\alpha > \beta$, $\partial^2\Pi_2^I/\partial d_2\partial d_1 > 0$ if $6\beta\alpha - 5\beta^2 - \delta > 0$, which solves for $6\sqrt{\Delta_2} > 5rZ_2^I + (\pi_{11} - \pi_{00})/(rZ_2^I)$. If this condition is not satisfied and $6\beta\alpha - 5\beta^2 - \delta < 0$ then $\partial^2\Pi_2^I/\partial d_2\partial d_1 < 0$ if γ is sufficiently large, which is equivalent to saying that π_{10} is greater than a certain critical threshold $\bar{\pi}_{10}$. ■

Proof of Proposition 8.5 (i) and (ii) We have that $\frac{\partial \Pi_2^C}{\partial d_1} = -\frac{K}{\sqrt{\Delta_1}}(\pi_{00} - \pi_{01})$ and $\frac{\partial \Pi_2^I}{\partial d_1} = K\frac{\sqrt{\Delta_2}}{\sqrt{\Delta_1^I}}\left(\frac{\pi_{11}-\pi_{00}}{\sqrt{\Delta_2}} - Z_2^I r\left(2 - \frac{rZ_2^I}{\sqrt{\Delta_2}}\right)\right)$. Thus, $\frac{\partial \Pi_2^I}{\partial d_1} > \frac{\partial \Pi_2^C}{\partial d_1}$ is equivalent to

$$\frac{\pi_{11}-\pi_{00}}{\Delta_2}\frac{\sqrt{\Delta_2}}{rZ_2^I} + \frac{rZ_2^I}{\sqrt{\Delta_2}} > 2 - \frac{\sqrt{\Delta_2}}{rZ_2^I}\frac{\pi_{00}-\pi_{01}}{\Delta_2}\frac{\sqrt{\Delta_1^I}}{\sqrt{\Delta_1}}.$$

In the limit as $\pi_{00} \to \pi_{01}$ we have

$$\frac{\partial \Pi_2^I}{\partial d_1} > \frac{\partial \Pi_2^C}{\partial d_1} \Leftrightarrow \frac{\sqrt{\Delta_2}}{rZ_2^I} + \frac{rZ_2^I}{\sqrt{\Delta_2}} > 2$$

and the second inequality always holds. For $\pi_{00} \to \pi_{11}$ we have $\Delta_1^I = \Delta_1 \frac{Z_2^I r}{\sqrt{\Delta_2}}$ and hence

$$\frac{\partial \Pi_2^I}{\partial d_1} > \frac{\partial \Pi_2^C}{\partial d_1} \Leftrightarrow \frac{rZ_2^I}{\sqrt{\Delta_2}} + \sqrt{\frac{\sqrt{\Delta_2}}{rZ_2^I}} > 2,$$

and the second inequality does not hold as $rZ_2^I < \sqrt{\Delta_2}$. ■

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