INNOVATION AND COMPLEMENTARY RESOURCE DEVELOPMENT UNDER THE THREAT OF IMITATION*

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Abstract. I study an innovator's incentives to innovate when a potential imitator has an initial advantage in a valuable complementary resource. The innovator may develop the complementary resource, but resource development takes time, so the innovator may obtain the resource before or after she innovates. I show the innovator may find it optimal to innovate even if the innovation is likely to be imitated before she develops the complementary resource. I also show the innovator may adapt to a low appropriability regime by *erecting barriers to imitation,* such as delaying the implementation of the innovation. I then consider technology-sharing decisions, and show the innovator finds it optimal to license the innovation to the imitator if she faces a *weak imitator* (that is, if the cost of imitation is large or the value of the complementary resource is small), and to keep the innovation secret until she develops the complementary resource if she faces a *strong imitator.* I also show a reduction in resource-development time decreases the probability the innovation is licensed and increases the probability of implementation delays.

Keywords: Resource-based view, Dynamic capabilities, Innovation, Resource development, Appropriability, Complementary resources, Imitation, Licensing.

Date: August 27, 2019.

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1. Introduction

The resource-based view is one of the most influential conceptual frameworks in the field of strategic management. This view asserts that competitive advantage is rooted in the possession of valuable resources that are rare and difficult to imitate (Wernerfelt, 1984; Barney, 1986, 1991; Dierickx and Cool, 1989; Mahoney and Pandian, 1992; Peteraf, 1993). Specific asset positions also shape managerial and organizational procedures that affect firms' dynamic capabilities–that is, their capacity to adapt to changing environments– through their impact on innovation performance and competition (Nelson and Winter, 1982; Teece and Pisano, 1994; Teece, Pisano, and Shuen, 1997).

Teece (1986) builds on ideas from Schumpeter (1935, 1942), Arrow (1962), and Williamson (1975) to show innovators may fail to capture the returns from an innovation if they do not have access to key complementary resources, such as production and marketing capabilities. As an example, consider Sony's pioneering development of electronic book readers in the early 2000s. Sony introduced the Librie in Japan in 2004 and the PRS-500 in the US in 2006. Amazon imitated the technical features of Sony's e-readers and introduced the Kindle in 2007. However, Sony's book repository was significantly smaller than Amazon's, which allowed Amazon to capture the e-reader market. As a consequence, Sony went from industry leader to leaving the industry in less than seven years.[1]

Recent works present game-theoretical models to study how resource advantages arise and are sustained (see, e.g., Makadok, 2001; Makadok and Barney, 2001; Pacheco-de Almeida and Zemsky, 2007; Grahovac and Miller, 2009; Chatain and Zemsky, 2011; Almeida Costa, Cool, and Dierickx, 2013; Chatain, 2014). The relation between innovation incentives and the development of complementary resources, on the other hand, has been studied less from a game-theoretical point of view, and is the main focus of this paper.

In this paper, I contribute to the resource-based view and dynamic-capabilities literatures by studying the incentives to innovate, implement innovations, develop complementary resources, and enter licensing agreements when a potential imitator has an initial advantage in a complementary resource.

I consider a dynamic model in which an innovator invests in R&D to develop an innovation and then decides the optimal time at which to bring the innovation to the market. Innovation is probabilistic and the probability of success depends on the innovator's research effort. Initially, the innovator lacks a valuable complementary resource, which she

[1]Similarly, MapQuest introduced the first online map service but was imitated and surpassed by Google (which provided a myriad of complementary services), and Joost introduced the first video-streaming service but was imitated and unseated by Hulu (which provided more complementary content obtained from TV and movie studios). See also the traditional examples of EMI, RC Cola, Xerox, and De Havilland in Teece (1986).

may develop by performing a costly investment. Resource development may involve the acquisition of intangible assets, the embodiment of new knowledge, or the creation of routines, all of which are time-consuming processes. Thus, the innovator may obtain the innovation before or after she obtains the complementary resource.

Bringing the innovation to the market discloses its existence and makes it possible for a rival firm (imitator) to try to imitate it. The threat of imitation is particularly relevant, since the imitator already owns the complementary resource, and would thus have a competitive advantage if she was to imitate before the innovator obtains the complementary resource. Therefore, the innovator may find it optimal to delay the implementation of a successful innovation until she develops the complementary resource.

I present four main results. First, I show an innovator may find it optimal to invest to develop and implement an innovation, even if the cost of imitation is low and the innovation is likely to be imitated before the innovator obtains a position in the complementary resource. This result contrasts with Teece's (1986) assertion that innovators may be "so ill positioned in the market that they necessarily will fail." In fact, I show such "failure" may be anticipated and optimally internalized by the innovator.

As an example, consider the Nintendo Wii gaming console, which was the first to include a remote controller with the ability to detect movement in three dimensions. The Wii had a less powerful processing engine than the PlayStation and Xbox, and Nintendo knew its innovation would be rapidly copied by Sony and Microsoft. However, Nintendo found it optimal to introduce its innovation and capture monopoly profits until it was imitated.

Second, I show innovators are not helpless in the face of imitation, as they may optimally respond to a greater threat of imitation by *erecting barriers to imitation*. In particular, I show that if the cost of imitation is low and the imitator's initial resource advantage is large, the innovator finds it optimal to delay the implementation of the innovation until she obtains the complementary asset. As a consequence, a lower cost of imitation may actually lead to a smaller probability of imitation. This result is absent in previous papers studying resource development in the face of imitation, because they do not endogenize the barriers to imitation.[2]

Third, I show that if technology licensing is possible, it may increase the probability of innovation and reduce implementation delays.[3] However, *licensing may fail* because the

[2]Pacheco-de Almeida and Zemsky (2007) show imitators may benefit from reducing the informational spillover they obtain from innovators because this enhances the innovator's incentives to develop innovations, and Grahovac and Miller (2009) show innovators may benefit if the value of the resource they want to develop is smaller because this may reduce imitation incentives. Neither paper studies the innovator's incentives to erect barriers to imitation. In contrast, I show a reduction in the cost of imitation may benefit the imitator because it lowers the innovator's incentive to delay the implementation of an innovation.

[3]For easiness of exposition, I focus on technology licensing but other technology-sharing agreements—such as a research joint venture or technology alliance—would lead to similar results.

innovator may have incentives to keep the innovation secret, instead of licensing it to the imitator.

The reason for this result is that approaching the imitator to negotiate a licensing agreement discloses the existence of the innovation. If the innovation is easy to imitate, the innovator has a weak bargaining position in licensing negotiations, in which case she prefers to keep the innovation secret and implement it on her own after she obtains the complementary resource, rather than licensing it to the imitator.

More surprisingly, I find licensing is more likely the larger the cost of imitation and the smaller the imitator's initial resource advantage. That is, I show *licensing is more likely when the innovator has a strong bargaining position* (i.e., the imitator has a weak bargaining position). This result is unexpected a priori because one would expect the innovator has more incentives to license the innovation if the innovation is easier to imitate (that is, one would expect licensing to be more likely when the innovator has a *weak* bargaining position).

Fourth, I show that a reduction in resource-development time increases the probability the innovation is implemented with delay. This link between the development of valuable resources and the implementation of complementary innovations had not been uncovered by previous works, and is caused by the optimal implementation dynamics discussed above.

Altogether, the paper's results suggest Sony employed a suboptimal strategy in the e-reader market. As explained above, Sony attempted to capture the market without having a strong position in the complementary resource. The above results imply that when contracting is feasible, two other strategies dominate Sony's adopted strategy: Sony could have kept the innovation secret and wait until it obtained the complementary resource, or it could have approached Amazon to negotiate a licensing agreement or technology alliance. Given that in the case at hand it was almost impossible to keep the innovation secret while trying to secure the distribution rights for thousands of books, the model suggests Sony's optimal strategy would have been to enter a technology-sharing agreement with Amazon.

The main contribution of this paper is to provide an integrated framework to study innovation, implementation, imitation, and licensing decisions in an imperfectly-competitive market. In doing so, I formalize Teece's (1986) analysis on the relationship of innovation and complementary resources, and provide further insights not present in the foundational works of the resource-based view and dynamic-capabilities literatures. In particular, I show resource-development and innovation strategies should be jointly designed to consider how external competition and imitation dynamics shape the firm's value creation and value capture potential. Providing this analysis is important because theory can make a significant contribution the development of management research, as articulated by Conner (1991), Mahoney and Pandian (1992), and Adner, Pólos, Ryall, and Sorenson (2009), among others.

1.1. **Related literature.** This paper builds upon the theory of resources (Wernerfelt, 1984; Barney, 1986, 1991; Dierickx and Cool, 1989; Mahoney and Pandian, 1992; Peteraf, 1993) and the theory of dynamic capabilities (Nelson and Winter, 1982; Teece and Pisano, 1994; Teece, Pisano, and Shuen, 1997). In particular, the paper studies the how the incentives to innovate are affected by the possession of complementary resources, an issue that was first studied by Teece (1986). To the best of my knowledge, Teece's (1986) ideas have not been formalized in a game-theoretical framework. I show studying a game-theoretical model yields additional insights that complement Teece's initial analysis.

The paper is also related with economics and strategy papers studying innovation, imitation, and technology adoption. The innovation literature has focused on substitute rather than complementary innovations (see, for example, Loury, 1979; Lee and Wilde, 1980; Gilbert and Newbery, 1982; Reinganum, 1982). Some exceptions are Gilbert and Katz (2011), Ménière (2008), Denicolò and Halmenschlager (2012), and D'Antoni and Rossi (2014), which focus on understanding the incentives to develop complementary innovations. Other significant contributions are Adner and Kapoor (2010) and Adner (2012), which show innovation ecosystems are important for developing complementary innovations. All these papers study complementary inventions developed by different firms, and do not study imitation and implementation decisions. In contrast, I study the incentives of one firm to develop and implement an innovation and a complementary resource in the face of imitation.[4]

Most papers studying the relationship between innovation and imitation assume imitation is exogenous, and focus on analyzing how imitation affects innovation incentives. Two important exceptions are Cohen and Levinthal (1989, 1990) and Gallini (1992), which endogenize imitation activities. Cohen and Levinthal (1989, 1990) show R&D activities affect the capacity to absorbe other firms' innovations. Gallini (1992) studies the effects of the patent regime on the incentives to innovate and imitate in a model with costly imitation. I do not consider absorptive capacity, and focus on firms' profitability. The strategic-adoption literature has studied the incentives to foreclose the market (Reinganum, 1981a,b; Fudenberg and Tirole, 1985; Ruiz-Aliseda and Zemsky, 2006) and the incentives to be a second mover to benefit from imitation (Katz and Shapiro, 1987). I complement the analysis of these papers by focusing on the incentives to delay the implementation (adoption) of an innovation to prevent imitation.

The closest papers to mine are Almeida Costa and Dierickx (2005), Pacheco-de Almeida and Zemsky (2007), and Grahovac and Miller (2009). Almeida Costa and Dierickx (2005)

[4]The paper is also related with the literature on cumulative innovation (Scotchmer, 1991, 1996; Green and Scotchmer, 1995; O'Donoghue, 1998; Denicolo, 2000). This literature studies the optimal division of profits between sequential innovators, and assumes that one innovation is essential for the other, but not the other way around. In Chen and Nalebuff's (2006) terminology, innovations are one-way essential complements. In the current paper, instead, the innovation and the complementary asset are not essential for each other.

study the optimal deployment strategy for innovation, but do not study innovation incentives, the timing of deployment, nor imitation. Pacheco-de Almeida and Zemsky (2007) and Grahovac and Miller (2009) study how the incentives to develop a resource are affected by the threat of imitation. I complement these papers by endogenizing the barriers to imitation, and by studying the incentives to develop complementary resources.

2. The model

Two firms, $i = 1, 2$, compete in periods $t \geq 0$ to sell products to consumers.[5] Firm 1 (the innovator) has an idea for an innovation that she may develop by investing in R&D. Firm 2 (the imitator) has an initial competitive advantage due to her possession of an exclusive resource or capability. This resource is complementary to the innovator's innovation, and firm 1 may invest to develop such resource, thereby eliminating its competitive disadvantage.

The main difference between innovation and resource development is that innovation is more uncertain than resource development. This difference reflects the traditional distinction between research and development (see, e.g., Katz and Shapiro, 1987). Even though resource development takes time, the firm is more certain as to what needs to be done to develop the resource (e.g., purchase assets, hire new employees, train existing employees, etc.). Innovation, on the other hand, is a probabilistic endeavor: even though the innovator may increase the probability of obtaining an innovation by increasing its investment in R&D, it is difficult to guarantee that an innovation will be obtained in a given period.

To model the difference between innovation and resource development in the simplest possible way, I assume that developing the complementary resource is a deterministic but time-consuming process, and that innovation is probabilistic. At time 0, the innovator knows she will obtain the complementary asset at time T. In the first part of the paper, I assume the resource-development deadline T is an exogenous parameter. In Section 5, I consider time-compression diseconomies and endogenize the decision to accelerate the complementary asset's development (that is, I endogenize T). Throughout the paper, I assume the innovator incurs in a small (negligible but positive) cost every period while she develops the complementary asset, which she can avoid if she halts development before obtaining the complementary resource.

At time t, the innovator obtains the innovation with probability p_t by incurring in an R&D cost of λp_t^2, where λ is a positive parameter. To focus on innovation and imitation dynamics, I assume that the innovator is the only firm with the capacity and knowledge necessary

[5]The infinite-time horizon assumption is not essential for the results of the paper. The main advantage of this assumption is that it allows me to avoid end-of-period effects. The model can be easily reinterpreted as a finite-horizon model with stochastic end by interpreting the discount factor as the probability the game lasts one more period.

to develop the innovation, and that the imitator does not learn about the existence of the innovation until it is *implemented* (that is, until the products that embed the innovation are introduced in the market). As I explain below, the discount factor can be interpreted as the probability that a superior innovation is introduced in the market—either before or after the focal firm innovates—rendering the firm's innovation obsolete. Thus, the discount factor represents the intensity of competition in the market for innovations.

After the innovation is implemented, the imitator can invest in R&D to imitate it. At time t, the imitator imitates the innovation with probability q_t by incurring in an R&D cost of $\mu\, q_t^2$, where μ is a positive parameter. I assume $\lambda > 1$ and $\mu > \frac{\alpha}{2\,(1-\delta)}$ to guarantee the existence of interior solutions to the R&D investment problems.

Given that implementing an innovation discloses its existence to the imitator, the innovator may have incentives to *delay the implementation* of an innovation. Therefore, after she innovates, the innovator must decide at which time to implement the innovation.

Firm 2's has zero marginal costs of production. Firm 1's marginal cost is $\alpha \in [0, 1]$ before she obtains the complementary asset, and is zero after she obtains the complementary asset. Thus, α represents the value of the imitator's initial *resource advantage*.

Each period, firms sell goods to a continuum of consumers of mass 1. Consumers have unit demands and are willing to pay $\omega > \alpha$ for a good without an innovation and $\omega' > \omega$ for a unit of a good with an innovation. Without loss, I normalize the innovation's impact on the willingness to pay to unity, so $\omega' = \omega + 1$.[6]

Given that consumers are homogeneous, Bertrand competition implies the market is winner-take-all. Thus, I focus on competition *for the market* and abstract from competition *in the market*. Clearly, this assumption is a good fit for many markets—such as the e-reader market described in the introduction—but less of a good fit in the case of other markets. Similar results would be obtained in a model with competition in the market, but analytical expressions and intuitions would be significantly more complex. The present paper intends to be a first step in the study of innovation and resource development under competition. Thus, I leave the extension of the paper's results under coexistence for future research.

Consumer utility equals willingness to pay minus price. A firm's per-period profit is equal to product-market revenues minus production costs and R&D expenditures. Firms discount future payoffs with a common discount factor $\delta \in [0, 1)$. As noted, the discount factor may be not only related to subjective payoff discounting, but also to the probability the market

[6]For easiness of exposition, I assume the complementary resource affects production costs. For example, the resource may be related to manufacturing capabilities and organizational routines that affect the firm's variable cost of production. It would be straightforward to modify the model to allow for initial differences in product quality. For example, it may be assumed that the complementary resource increases consumers' willingness to pay in α. Results would be analogous with this alternative specification.

for the innovation ends due to the change in consumer preferences, or to the probability a superior innovation is introduced in the market.

Within each period, firms play a four-stage game. First, if firm 1 has not innovated, she chooses its investment in R&D and the innovation outcome is realized. Second, if firm 1 has obtained but not implemented the innovation, she decides whether to implement it. Third, if firm 1 has implemented the innovation and firm 2 has not imitated, firm 2 chooses her investment in R&D and the imitation outcome is realized. Fourth, firms compete in prices. Figure 1 summarizes gameplay within each period. The solution concept is subgame-perfect equilibrium.

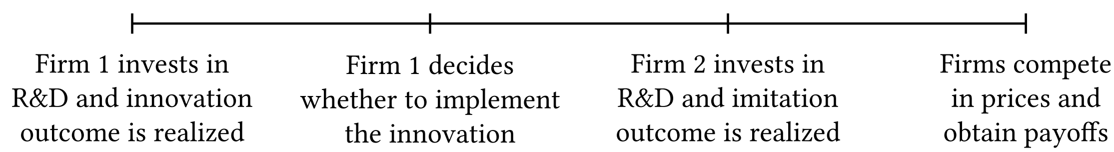


FIGURE 1. Timing within each period.

3. SOLUTION OF THE MODEL

In this section, I provide an informal discussion of the main results of the basic model. For technical details–along with proofs–see Appendix A. I begin by providing a short description of the steps needed to solve the model.

The model is solved by backward induction, and I begin by considering price competition. At any given period, equilibrium prices and profits depend on the possession of the innovation and the complementary resource. Table 1 presents equilibrium prices and product-market profits (revenues net of production costs).[7]

Second, I consider the innovator's optimal R&D investment at a decision node after she obtains the complementary resource. Such decision node would be reached if the innovator failed to innovate before obtaining the complementary resource.

Third, I consider the imitator's optimal R&D investment at a decision node after the innovator implements the innovation. After the innovator obtains the complementary resource,

[7]If at time t both firms have the complementary asset and either both or none have the innovation, firms are in competitive parity, equilibrium price is equal to marginal cost (zero), and firms obtain zero profits. If firm 2 has a resource advantage and firm 1 has not implemented the innovation, equilibrium price is equal to firm 1's marginal cost, firm 2 has a profit of α, and firm 1 has a profit of zero. If firm 1 has implemented the innovation and firm 2 has a resource advantage, firm 1 chooses a price of 1 and obtains a profit of $1-\alpha$, and firm 2 chooses a price of 0 and obtains a profit of 0. If firm 1 has implemented the innovation and has developed the complementary asset, firm 1 chooses a price of 1 and obtains a profit of 1, and firm 2 chooses a price of 0 and obtains a profit of 0. If firm 1 has implemented the innovation and firm 2 has imitated it, equilibrium price is equal to α, firm 2 has a profit of α, and firm 1 has a profit of zero.

		Firm 1 (innovator)			
		Has not implemented innovation		Has implemented innovation	
		Does not have complementary asset	Has complementary asset	Does not have complementary asset	Has complementary asset
Firm 2 (imitator)	Does not have innovation	$r_{1t} = r_{2t} = \alpha$, $F_{1t} = 0$, $F_{2t} = \alpha$	$r_{1t} = r_{2t} = 0$, $F_{1t} = F_{2t} = 0$	$r_{1t} = 1$, $r_{2t} = 0$, $F_{1t} = 1 - \alpha$, $F_{2t} = 0$	$r_{1t} = 1$, $r_{2t} = 0$, $F_{1t} = 1$, $F_{2t} = 0$
	Has innovation			$r_{1t} = r_{2t} = \alpha$, $F_{1t} = 0$, $F_{2t} = \alpha$	$r_{1t} = r_{2t} = 0$, $F_{1t} = F_{2t} = 0$

TABLE 1. Equilibrium prices (r_{it}) and profits (F_{it}) in period t.

the imitator will not invest to imitate the innovation because in that case a successful imitation would only lead to competitive parity and zero profits. Thus, the imitator's R&D investment can be positive only before T.

Fourth, I consider the innovator's decision to implement the innovation at a decision node after she obtains the innovation. This decision takes into account the imitator's optimal imitation effort if the innovation is implemented. Note it is always optimal to implement an innovation immediately (in the same period it is obtained) if the innovation is obtained at or after T, because in this case the imitator will not attempt to imitate it. The implementation decision is more complex before T, because in this case, the innovator must balance a trade-off between current product-market revenues and risk of imitation.

Finally, I consider the innovator's optimal R&D investment at a decision node before she obtains the complementary resource. The optimal investment takes into account the optimal implementation decision in case of a successful innovation, which, in turn, takes into account the imitator's optimal imitation effort.

Proposition 1 describes equilibrium dynamics. For a detailed proof, see Appendix A.

Proposition 1 (Equilibrium dynamics)**.** *An equilibrium exists and is unique. Equilibrium dynamics are as follows.*

Imitation dynamics: *The probability of imitation increases as time t moves closer to the resource-development deadline T, and is equal to zero after T.*

Implementation dynamics: *There exists a threshold $\hat{\mu}$ for the imitation cost parameter μ such that if $\mu \geq \hat{\mu}$ the innovation is implemented immediately (in the same period it is obtained), and if $\mu < \hat{\mu}$, there exists a threshold $t^* < T$ such that the innovation is* *implemented with delay (at time T) if it is obtained at $t \in [t^*, T)$ and is implemented immediately otherwise.*

Innovation dynamics: *The probability of innovation is constant for $t \geq T$. If the innovation is to be implemented immediately, the probability of innovation may increase or decrease with t for $t < T$. If the innovation is to be implemented with delay, the probability of innovation increases with t for $t < T$.*

Profit dynamics: *The innovator's expected profit before innovation increases as time t moves closer to the resource-development deadline T, and is constant afterwards. The imitator's expected profit before imitation decreases as t moves closer to T, and is zero afterwards.*

Proposition 1 has two main implications. First, the proposition shows an innovator may find it optimal to invest to develop and implement an innovation, even if the cost of imitation is low and the innovation is likely to be imitated before the innovator obtains a position in the complementary resource.

This result contrasts with Teece's (1986) assertion that innovators may be "so ill positioned in the market that they necessarily will fail." Proposition 1 shows such "failure" may be anticipated by and optimally internalized by the innovator; that is, the innovator may implement the innovation even if she knows the innovation is likely to be imitated before she obtains the complementary resource.

More strikingly, for some values of the parameters, an innovation will be brought to market only if the date at which the innovator obtains the innovation is sufficiently far away from the date she obtains the complementary resource, which actually implies the innovation is very likely to be imitated. This result is interesting because at priori one would expect the innovator to have incentives to implement the innovation only if the innovation is unlikely to be imitated.

Second, the proposition shows innovators are not helpless in the face of imitation, as they may respond to a greater threat of imitation by erecting barriers to imitation. If the cost of imitation is low and the initial resource advantage of imitators is large, the innovator will find it optimal to delay the implementation of the innovation until she obtains the complementary asset.

As a consequence of this result, a decrease in the cost of imitation may actually decrease the probability of imitation in equilibrium. This result is absent in previous papers studying resource development in the face of imitation (Pacheco-de Almeida and Zemsky, 2007; Grahovac and Miller, 2009), because they do not endogenize barriers to imitation.

In the following subsections I discuss the results of Proposition 1 in more detail. I begin by considering imitation dynamics.

Imitation dynamics. Imitation dynamics depend on the time available until the innovator obtains the complementary resource. As the resource-development deadline nears, the need to imitate becomes more imperative, and the imitator increases its investment in R&D.

In formal terms, the optimal imitation effort solves the following Bellman equation:

$$W_t = \max_{q_t \in [0,1]} \left(q_t \frac{\alpha}{1-\delta} + (1-q_t)\,\delta\, W_{t+1} - \mu\, {q_t}^2 \right),$$

where W_t is the imitator's expected profit before imitation in period t.[8] The "consolation prize" of failing to imitate is the possibility of attempting an imitation in the next period, which has a discounted value of $\delta\, W_{t+1}$. Given that this continuation value decreases as the deadline T approaches (because the imitator's expected profit W_t is smaller the closer she is to T), the imitator's investment incentives increase with t.

Implementation dynamics. Implementation dynamics are depicted in Figure 2. The horizontal line represents the time at which the innovation is obtained. Proposition 1 shows there exists an implementation threshold t^* such that the innovator implements the innovation immediately (in the same period she obtains it) if she innovates before this threshold, and implements the innovation with delay if she innovates after this threshold.

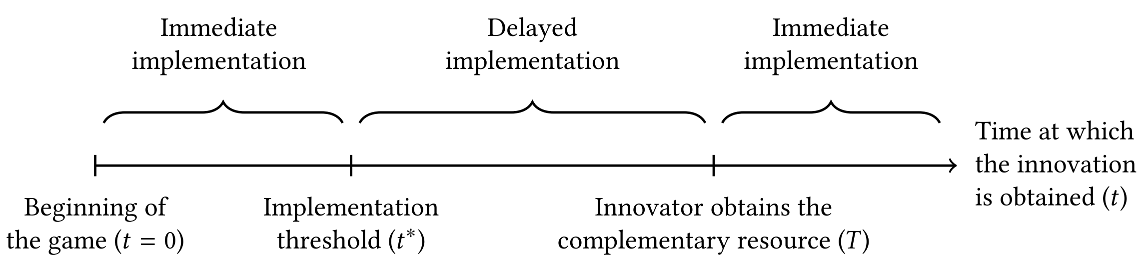


Figure 2. Implementation dynamics. The innovator implements the innovation immediately if she obtains it before t^* or after T. Otherwise, she implements the innovation with delay.

The implementation decision is affected by a *trade-off between short-term and long-term profitability:* Implementing the innovation before T implies the innovator can obtain product-market revenues earlier but, at the same time, enables imitation from rivals. If the innovator innovates long before resource-development deadline, she prefers to implement the innovation immediately and benefit from having positive profits in the short term, even though doing so will probably mean the innovation will be imitated before she obtains the complementary asset. If the innovator innovates close to the date at which she will obtain the

[8] To understand this equation, note that with probability q_t, the imitator succeeds and obtains the discounted flow of future benefits $\frac{\alpha}{1-\delta}$, and with probability $1-q_t$, the imitator fails and obtains the discounted continuation value $\delta\, W_{t+1}$. See Section A.2 for more details.

complementary resource, she prefers to wait to prevent imitation and benefit from future profits.

The resolution of this trade-off depends on the imitation-cost parameter μ and the imitator's resource advantage α. If the imitation cost is large, the trade-off is resolved in favor of present profitability and the innovator implements any innovation immediately. If the imitation cost is small, the implementation trade-off is resolved in favor of future profitability and the innovator delays the implementation of any innovation. For intermediate values, the resolution of the trade-off depends on how close the resource-development deadline is, and the innovation is implemented only if the innovator is sufficiently far from T.[9] Finally, given an imitation cost, if the resource advantage is large (small), product-market revenues are small (large) before T, and the innovator prefers to delay implementation (implement immediately). Figure 3 illustrates these results.

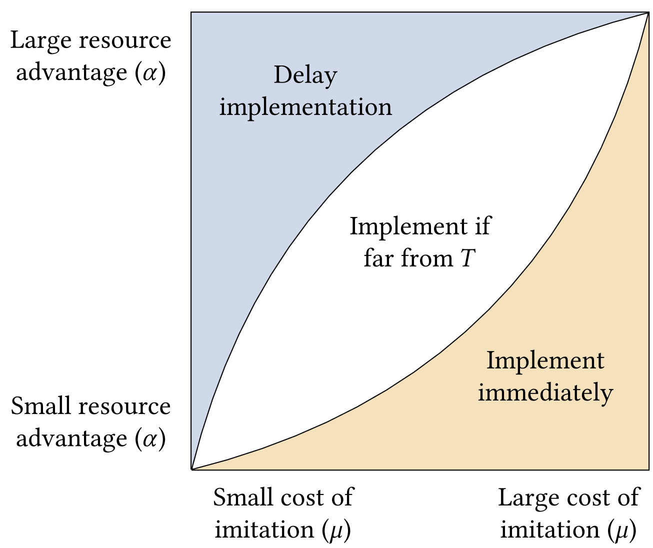


FIGURE 3. Implementation decision. If the imitator's resource advantage is large, the innovator implements the innovation with delay. If the cost of imitation is large, the innovator implements the innovation immediately. For intermediate values of the parameters, the innovator implements the innovation immediately only if she obtains it sufficiently far away from T.

[9]Formally, if μ is large, $t^* = T$; if μ is small, $t^* = 0$; and for intermediate values of μ, $0 < t^* < T$.

Innovation dynamics. Innovation dynamics depend on the innovator's implementation decision and on the imitator's optimal imitation effort if the innovation is implemented before T. The innovator's investment solves the following Bellman equation:

$$V_t = \max_{p_t \in [0,1]} \left(p_t\, Y_t + (1 - p_t)\, \delta\, V_{t+1} - \lambda\, {p_t}^2\right),$$

where V_t is the innovator's expected profit before innovation, and Y_t is the innovator's expected profit for innovating at time t.

As the resource-development deadline nears, the profit from a successful innovation (Y_t) increases, which tends to increase the innovator's R&D investment. However, as T becomes closer, the continuation value from not innovating V_{t+1} also increases, which tends to decrease investment. Thus, R&D investment may increase or decrease with t. In Appendix A, I show this last result is only possible if the innovation would be implemented immediately if it was obtained at t. If implementation would be delayed, the first effect is always larger than the second, and the probability of innovation increases with t.

4. Licensing and technology transfer

In order to avoid spending time and resources to develop the complementary asset, the innovator can license the innovation to the imitator, purchase the complementary asset from her, or create a technology alliance. Contracting with the imitator avoids these inefficiencies, and can potentially increase expected profits for both firms.

For the innovator, an unwanted consequence of proposing a technology-sharing agreement to the imitator is that the imitator learns of the innovation's existence, and can try to imitate it if firms do not reach an agreement. Thus, the mere act of discussing a licensing agreement, attempting to buy the complementary good, or proposing to create an alliance affects firms' outside options and the value they capture in equilibrium.[10]

For concreteness, I assume that after the innovator innovates, she can offer an exclusive license to the imitator, and that firms negotiate licensing terms a la Nash with equal bargaining coefficients. As in the previous section, I present an informal discussion. For technical details and proofs, see Appendix B.

If the innovator innovates in period $t < T$, she can choose to implement the innovation immediately, wait until a later time to implement it, or approach the imitator to discuss a licensing agreement. In period T, the innovator obtains the complementary asset. Thus, there is no room for contracting for innovations obtained in $t \geq T$.

[10]For concreteness, I focus on the problems caused by information disclosure on the private desirability of contracts (Arrow, 1962). Contracting may be difficult for other reasons, such as the need for relationship-specific investments (Williamson, 1975; Teece, 1986). Incorporating these assumptions in the analysis would be straightforward and would not alter its main qualitative implications.

Suppose the innovator innovates in $T-1$. If the innovator offers a license to the imitator and firms reach an agreement, they create a joint total value of $1/(1-\delta)$. If firms fail to reach an agreement, the best the innovator can do is to implement the innovation without the complementary resource. If the innovation is not imitated, the innovator obtains $1-\alpha$ in $T-1$, and a flow payoff of 1 from period T onwards. Therefore, the innovator's outside option is

$$O^1_{T-1} = \left(1 - q^*_{T-1}\right)\left(1 - \alpha + \delta\,\frac{1}{1-\delta}\right),$$

where q^*_{T-1} is the equilibrium probability the imitator imitates the innovation. If bargaining fails, the best the imitator can do is to try to imitate the innovation. If she imitates the innovation, she obtains a flow payoff of α, and if she fails she obtains zero (the imitator will not invest to imitate the innovation in $t \geq T$). Thus, the imitator's outside option is

$$O^2_{T-1} = \max_{q_t \in [0,1]} \left(q_t \frac{\alpha}{1-\delta} - \mu\, q_t^2\right).$$

It is straightforward to see the imitator's optimal investment in R&D in case of no agreement is $q^*_{T-1} = \alpha/(2\mu(1-\delta))$. Firm i's bargaining payoff at $T-1$ is

$$R^i_{T-1} = O^i_{T-1} + \frac{1}{2}\left(\frac{1}{1-\delta} - O^1_{T-1} - O^2_{T-1}\right).$$

Working with the above expressions, I obtain the innovator's bargaining payoff:

$$\begin{aligned} R^1_{T-1} \quad &= \quad \left(1 - \frac{\alpha}{2\,\mu\,(1-\delta)}\right)\left(1 - \alpha + \frac{\delta}{1-\delta}\right) \\ &\quad + \frac{1}{2}\left(\frac{1}{1-\delta} - \left(1 - \frac{\alpha}{2\,\mu\,(1-\delta)}\right)\left(1 - \alpha + \frac{\delta}{1-\delta}\right) - \frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta}\right)^2\right). \end{aligned}$$

Instead of offering a license to the imitator, the innovator can market the innovation on her own (either at $T-1$ or at T), in which case the payoff from innovating would be the same as in the previous section. If the payoff from self-implementation is larger than the negotiated licensing payoff, the innovator prefers not to license. Clearly, this result is only possible if the innovator would implement in T if licensing was not available, because if the innovator would implement at $T-1$ without licensing, negotiating with the imitator always yields a positive bargaining surplus.

If the innovator implements the innovation at T, she obtains a total payoff of $1/(1-\delta)$ in that period. Thus, if the innovator obtains the innovation at $T-1$ and implements it at T, she obtains a discounted payoff of $\delta/(1-\delta)$. Therefore, the innovator chooses to market the innovation herself if $\delta/(1-\delta) > R^1_{T-1}$. Working with this inequality, I obtain Proposition 2. See Appendix B for a proof. In what follows, recall $\hat{\mu}$ is given in Proposition 1.

Proposition 2 (Licensing failure)**.** *Given $\delta > \frac{1}{4}$, there exist $\tilde{\alpha} \in (0,1)$ and $\tilde{\mu} \in \left(\frac{1}{2\,(1-\delta)}, \hat{\mu}\right)$ such that if $\alpha > \tilde{\alpha}$ and $\mu < \tilde{\mu}$, the innovator prefers to implement an innovation obtained in $T-1$ in period T, rather than licensing it to the imitator.*

Proposition 2 shows licensing may fail to materialize in equilibrium. Attempting to negotiate an agreement with the imitator discloses valuable information which affects the innovator's bargaining position. If the cost of imitation is small, the innovator anticipates a weak bargaining position in its negotiations with the imitator, and thus prefers to keep the innovation secret.

In the proof of Proposition 2, I show the threshold for the imitation cost that determines the no-contracting result is

$$\tilde{\mu} = \frac{\alpha\,(2-\alpha\,(1-2\,\delta))}{4\,(2-\alpha)\,(1-\delta)^2},$$

which implies the no-contracting result becomes more likely as the imitator's resource advantage α or the discount factor δ become larger.

More surprisingly, Proposition 2 shows licensing is more likely to fail the smaller the cost of imitation. This result goes against what a superficial analysis would yield: one would expect that if the innovation is easier to imitate the innovator has more incentives to license it. On the contrary, I show that if imitation is inexpensive, the innovator has a weak bargaining position in the licensing negotiations, and thus, she prefers to refrain from licensing the innovation. Similarly, I show licensing is more likely to fail the larger the imitator's initial resource advantage.

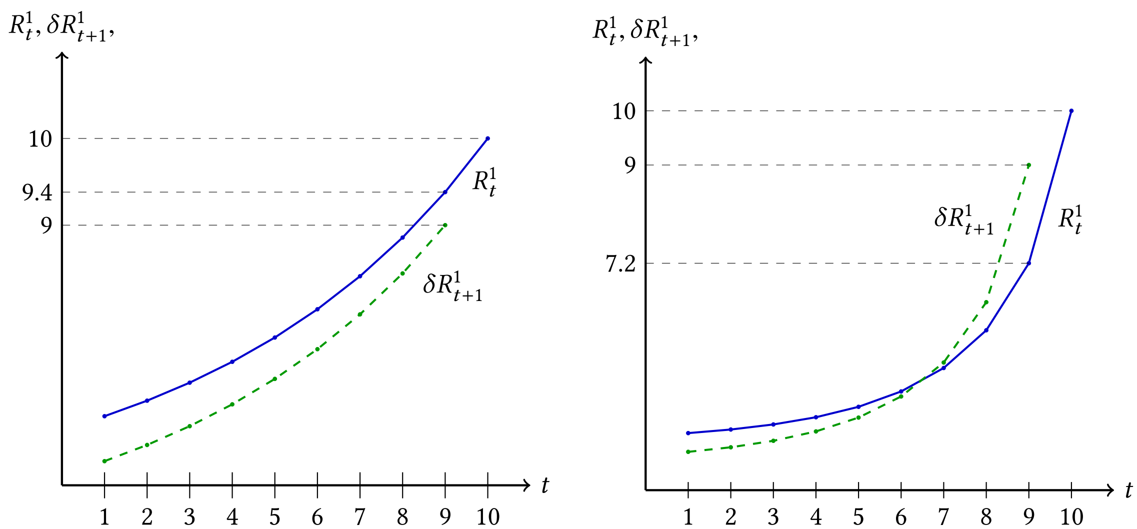
For innovations in $t < T-1$, bargaining payoffs are more difficult to obtain, because outside options are determined recursively. In particular, the innovator's best alternative to an agreement in $t < T-1$ is to implement the innovation in t and try to negotiate another agreement in $t+1$, and the imitator's best alternative is to try to imitate the innovation in t and, if she fails to imitate in t, try to negotiate another agreement in $t+1$.

Bargaining payoffs R_t^i can be obtained iterating backwards from the ones obtained for period $T-1$ (see Appendix B for details). Recall the decision to license is interesting only if the innovation would be implemented with delay in the absence of licensing (that is, only if $t^* \leq t \leq T-1$, where t^* is the implementation threshold of Proposition 1).

The above result implies that, if the innovator chooses not to license in t, she does not implement the innovation and must again decide whether to license the innovation in $t+1$. The payoff from licensing in t is R_t^1, and the payoff from licensing in $t+1$ is R_{t+1}^1. Therefore, $\delta\, R_{t+1}^1$ measures the value that the innovator captures in t if she waits to negotiate with the imitator until $t+1$.

Figure 4 shows R_t^1 (solid blue line) and δR_{t+1}^1 (dashed green line) for different values of the parameters. If μ is large, then $R_t^1 > \delta R_{t+1}^1$ for all t, and the innovator prefers to license the innovation as soon as she obtains it. This is the case in Figure 4a, for example.[11]

If μ is small, then $R_t^1 < \delta R_{t+1}^1$ for t close to T, in which case the innovator prefers to avoid licensing negotiations. In Figure 4b, for example, $\delta R_{t+1}^1 < R_t^1$ for $t \leq 6$, so the innovator licenses the innovation if she innovates at or before $t = 6$ and waits until T to implement the innovation if she innovates at a later date.[12]



(A) $\alpha = 0.75$, $\delta = 0.9$, $\mu = 100$, $T = 10$.

(B) $\alpha = 0.75$, $\delta = 0.9$, $\mu = 10$, $T = 10$.

FIGURE 4. Firm 1's incentives to negotiate a licensing agreement.

The above analysis implies that for small μ, there exists a threshold $\tilde{t} \geq t^*$, such that innovations are licensed only if they are obtained before $\tilde{t}$. Figure 5 shows licensing dynamics (the licensing decision does not depend on t^* or T, but I include these variables for comparison with Figure 2).

Finally, it is interesting to reflect on the positive effects of licensing, whenever it is an equilibrium outcome. If licensing is an equilibrium outcome, then it increases the innovator's expected payoff from innovation, and thus, it increases innovation expenditures. Licensing also improves implementation incentives: Innovations obtained in $t \in [t^*, \tilde{t})$ would be

[11] In Figure 4a, the payoff of implementing the innovation in T is $R_T^1 = 10$. Thus, the innovator obtains $\delta R_T^1 = 9$ in $T - 1$ if she waits until T to implement the innovation. If the innovator licenses the innovation in $T - 1$, she obtains a payoff of $R_{T-1} = 9.4$ which is larger than the discounted payoff of waiting, and thus the innovator licenses the innovation in $T - 1$.

[12] In Figure 4b, if the innovator licenses the innovation at $T - 1$, she obtains $R_{T-1} = 7.2$, which is smaller than the discounted payoff of waiting, $\delta R_T^1 = 9$, and thus the innovator prefers not to license the innovation.

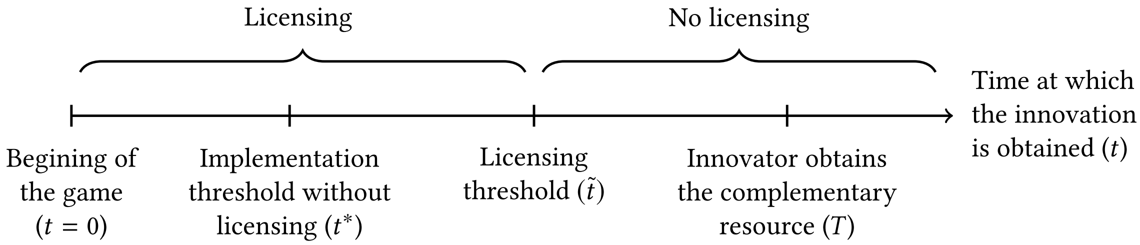


Figure 5. Licensing dynamics. The innovator licenses the innovation if she obtains it before $\tilde{t}$. Otherwise, she implements the innovation on her own.

implemented with delay without licensing, and are implemented immediately with licensing. Figure 6 illustrates this section's results (the dashed lines represent the implementation thresholds in the model without licensing).

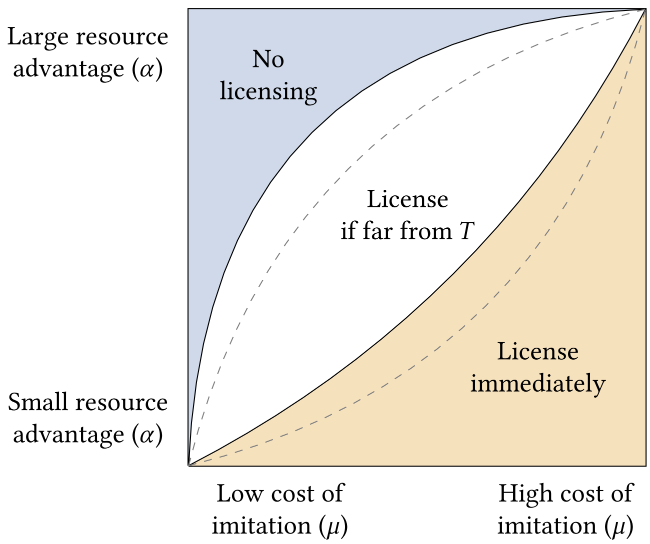


Figure 6. Licensing decision. If the imitator's resource advantage is large, the innovator does not license the innovation. If the cost of imitation is large, the innovator licenses the innovation immediately. For intermediate values of the parameters, the innovator licenses the innovation only if she obtains it sufficiently far away from T.

5. Incentives to invest in the complementary asset

In this section, I study equilibrium dynamics when the innovator can invest to reduce the time at which she will obtain the complementary resource. Lowering the resource-development time is generally costly due to time-compression diseconomies (Scherer, 1967; Dierickx and Cool, 1989; Pacheco-de Almeida and Zemsky, 2007). Thus, assume obtaining the complementary asset in period T implies a fixed cost $c_T \geq 0$, which is non-increasing in

T. The innovator chooses the development time before choosing its investment in R&D in period $t = 0$, and then the game proceeds as in the previous sections.

I proceed in two steps. First, I study the effects of changes in T on innovation, implementation and imitation incentives. Second, I study the effects of changes in the parameters on the optimal development time. As in the previous sections, I present an informal discussion. For a technical analysis, see Appendix C.

Before presenting results, I introduce some useful definitions (see Appendix C for more details). The *overall probability of imitation* is the probability the imitator imitates the innovator's innovation at some period, and the *probability of an implementation delay* is the probability that the innovator implements an innovation with delay.

For the next proposition, I focus on parameter values such that an innovation may be implemented immediately or with delay, depending on when it is obtained (that is, $0 < t^* < T$). For a given value of the imitator's initial resource advantage α, this result is obtained for intermediate values of the imitation cost parameter μ.[13]

Proposition 3 (Effects of a decrease in resource-development time)**.** *Suppose* $0 < t^* < T$. *A unit decrease in the resource-development time increases the expected profit of the innovator, decreases the overall probability of imitation, and increases the probability of an implementation delay.*

A decrease in the resource-development time increases the expected profit of the innovator at time 0. The innovator will be willing to invest to decrease the developing time if the cost associated with this decrease is smaller than the increase in her expected profit. A decrease in development time also lowers the probability the innovation will be imitated, given that a smaller T gives the imitator less time to try to imitate the innovation.

A more interesting result is that a reduction in development time increases the probability the innovation is implemented with delay. This link between the development of valuable resources and the implementation of complementary innovations had not been uncovered by previous works and is due to the optimal implementation dynamics studied in Section 3. For intermediate values of the cost of imitation, the innovator implements the innovation only if she is sufficiently far away from T. Lowering T implies the innovation is more likely to be obtained closer to the date at which the innovator obtains the complementary asset, and thus, an implementation delay becomes more likely.

[13] If $t^* = T$, the innovation is always implemented immediately (before and after the change in T), in which case the probability of an implementation delay is zero, and a unit reduction in T decreases the overall probability of imitation. If $t^* = 0$, the innovation is always implemented with delay if it is obtained before T (before and after the change in T), in which case the overall probability of imitation is zero, and a unit decrease in T decreases the probability of an implementation delay.

I now turn to the analysis of the effects of changes in the parameters on the optimal development time. For tractability, I assume $c_0 > 0$ and $c_t = 0$ for $t \geq 1$, and focus on the choice between $T = 0$ and $T = 1$.

Proposition 4 (Optimal resource-development time)**.** *The optimal development time is weakly increasing in the innovation-cost parameter λ. If $\mu \geq \hat{\mu}$, the optimal development time is weakly decreasing in the imitator's resource advantage α and weakly increasing in the imitation-cost parameter μ. If $\mu < \hat{\mu}$, the optimal development time is independent from α and μ, and is weakly decreasing in the discount factor δ.*

The result that the optimal development time is weakly increasing in λ is a consequence of the complementarity of the investments in the innovation and the complementary asset: a larger λ decreases the investment in R&D, which decreases the incentives to invest to obtain the complementary asset sooner.

If $\mu \geq \hat{\mu}$, the innovator implements any innovation in the same period she obtains it. Thus, regardless of whether $T = 0$ or $T = 1$, the innovator implements an innovation she obtains at $t = 0$ in that same period. If $T = 1$, the payoff the innovator obtains from implementing an innovation in $t = 0$ is smaller because: (1) at $t = 0$ the innovator does not have the complementary resource, and (2) by implementing before T, there is a risk the imitator imitates the innovation. As α increases, the payoff from early implementation decreases and the probability of imitation at increases. Both effects decrease the expected profit from innovation when $T = 1$ and have no impact when $T = 0$. Thus, as α increases, the innovator has more incentives to speed up development of the complementary resource. An increase in μ has the opposite effects.

Finally, if $\mu < \hat{\mu}$, the change in δ increases the total payoff of having both the innovation and the complementary asset, and thus increases the desirability of having the complementary asset. Although I have not been able to obtain a similar analytic result for the case $\mu > \hat{\mu}$, numerical simulations show the comparative statics with respect to δ extend to this case (that is, an increase in δ weakly decreases the optimal development time).

6. Low cost of imitation

In previous sections, I assumed the imitation-cost parameter was large enough to guarantee the imitator's profit maximization problem had an interior solution (i.e., $q_t^* \in (0, 1)$ for all t). In this section, I assume $\mu < \frac{\alpha}{2-\delta}$, which implies the imitator's maximization problem has a corner solution: The imitation cost is so small that the imitator chooses to imitate with probability 1. The solution of the model is otherwise analogous to that of previous sections.

In the following proposition, the overall probability of licensing is the probability that an innovation is licensed from $t = 0$ onwards. See Appendix D for a proof.

Proposition 5 (Low cost of imitation). *If $\mu < \frac{\alpha}{2-\delta}$, the probability of imitation is equal to 1 for all $t < T$. If the innovator innovates at time $t < T$ and licensing is not possible, she always implements the innovation with delay. If licensing is possible, there exists $\tilde{t} < T$ such that the innovator licenses the innovation immediately if she innovates before $\tilde{t}$, and implements the innovation at T otherwise. The overall probability of licensing increases with the imitation-cost parameter μ and decreases with the imitator's resource advantage α. Given α, μ, and T, if the discount factor δ is large enough, the innovation is never licensed.*

If licensing is not possible, the innovator will not implement the innovation until she finishes development of the complementary asset, because she knows an implemented innovation would be immediately imitated by the imitator. If licensing is possible, the innovator will license the innovation only if her bargaining position is strong enough when negotiating with the imitator, which implies the cost of imitation has to be sufficiently large and the resource advantage sufficiently small.

The assumption $\mu < \frac{\alpha}{2-\delta}$ allows for the study of the limit $\delta \to 1$ for fixed α and μ. When the innovator licenses the innovation, she obtains only a fraction of the product-market profits. As δ increases, product-market revenues increase and the opportunity cost of waiting to implement the innovation decreases. These effects make licensing less desirable for the innovator, and if δ is large enough the innovator does not license the innovation at any period. Likewise, licensing becomes less desirable as μ decreases or α decreases (see the proof of Proposition 5 for details).

7. Conclusion

The resource-based view of the firm is one of the main theoretical underpinnings of the field of strategic management. In this paper, I contribute to this literature by studying how the development of valuable resources interacts with the incentives to innovate and bring to market complementary inventions.

I present a model in which an innovator invests in R&D to develop an innovation, and then decides the optimal time at which to implement the innovation (i.e., introduce it in the market). The return to the innovation depends on the possession of a complementary asset, which the innovator does not have and needs to develop. The development of the complementary asset is done under the threat of imitation from rivals that possess the complementary resource, and thus would be in a position of advantage over the innovator if they were to imitate the innovation before the innovator has the complementary asset.

I present four main results. First, I show an innovator may find it optimal to invest to develop and implement an innovation, even if the cost of imitation is low and the innovation is likely to be imitated before the innovator obtains a position in the complementary resource. This result contrasts with Teece's (1986) assertion that innovators may be "so ill positioned in the market that they necessarily will fail." In fact, I show such "failure" may be anticipated and optimally internalized by the innovator.

Second, I show barriers to imitation are endogenous and affected by competitive interaction. Thus, innovators are not helpless in the face of imitation. If the cost of imitation is low and the initial resource advantage of imitators is large, the innovator will find it optimal to delay the implementation of an innovation until she finishes the development of the complementary asset. As a consequence, a lower cost of imitation may actually lead to a smaller probability of imitation.

Third, I show that licensing the innovation to a potential imitator may increase the probability of innovation and reduce implementation delays. However, licensing may fail because the innovator may have a small bargaining power when negotiating a licensing agreement. Therefore, the innovator may prefer to keep the innovation secret and wait until she has the complementary resource to introduce it in the market, rather than approaching a potential imitator to negotiate a licensing agreement. Interestingly, I find that licensing is more likely to fail the smaller the cost of imitation and the larger the imitator's initial resource advantage.

Fourth, I show that a reduction in the resource-development time increases the probability the innovation is implemented with delay. This link between the development of valuable resources and the implementation of complementary innovations had not been uncovered by previous works.

The main contribution of this paper is to provide an integrated framework to study innovation, implementation, imitation, and licensing decisions. I formalize Teece's (1986) analysis on the relationship of innovation and complementary resources, and provide further insights not present in the foundational works of the resource-based view and dynamic-capabilities literatures.

Appendix A. Solution of the basic model

In the following sections, I study innovation, imitation, and implementation decisions at different decision nodes. See the main text for the analysis of price competition. The main results follow from lemmas 1, 2, and 3, which also contain some additional results not included in the main text. I conclude by presenting the proof of Proposition 1.

A.1. **Firm 1 has the complementary asset but has not innovated.** Suppose the innovator has not obtained the innovation, and is choosing its innovation effort in $t \geq T$.

As long as the innovator does not innovate, firms are in competitive parity and both obtain a profit of 0. If the innovator innovates and implements the innovation, the imitator will not invest in R&D because a successful imitation would only lead to competitive parity and zero profits. Thus, if the innovator innovates in period $t \geq T$, she implements the innovation immediately and obtains a discounted sum of payoffs of $\frac{1}{1-\delta}$.

Let V_t be the innovator's expected profit in period t. For $t \geq T$, V_t satisfies the following Bellman equation:

$$V_t = \max_{p_t \in [0,1]} \left(p_t \frac{1}{1-\delta} + (1-p_t)\,\delta\, V_{t+1} - \lambda\, {p_t}^2 \right).$$

The first order condition is

$$\frac{1}{1-\delta} - \delta\, V_{t+1} - \lambda\, 2\, p_t = 0,$$

and the optimal probability of innovation at t is

$$p_t^* = \frac{1}{2\,\lambda} \left(\frac{1}{1-\delta} - \delta\, V_{t+1} \right). \tag{1}$$

Firm 1's expected profits evolve according to the difference equation

$$V_t = \delta\, V_{t+1} + \frac{1}{4\,\lambda} \left(\frac{1}{1-\delta} - \delta\, V_{t+1} \right)^2.$$

It is straightforward to see that the problem is stationary. Thus, the optimal probability of innovation $p_t^* = p_{t+1}^* = p_\infty^*$ is

$$p_\infty^* = \frac{1}{\lambda\,(1-\delta) + (\lambda^2\,(1-\delta)^2 + \lambda\,\delta)^{1/2}},$$

and expected profit $V_t = V_{t+1} = V_\infty$ is

$$V_\infty = \frac{2\,\lambda\,(1-\delta) + \frac{\delta}{1-\delta} - 2\,\left(\lambda^2\,(1-\delta)^2 + \lambda\,\delta\right)^{1/2}}{\delta^2}.$$

The assumption $\lambda > 1$ guarantees that $p_\infty^* < 1$. As λ increases, it becomes more costly to invest in R&D, and the optimal probability of innovation and expected profit decrease.

By the envelope theorem,

$$\frac{\partial V_t}{\partial \delta} = p_t \frac{1}{(1-\delta)^2} + (1-p_t)\, V_{t+1} + (1-p_t)\,\delta\, \frac{\partial V_{t+1}}{\partial \delta},$$

which implies

$$\frac{\partial V_\infty}{\partial \delta} = \frac{p_\infty^* \frac{1}{(1-\delta)^2} + (1-p_\infty^*)\, V_\infty}{1-(1-p_\infty^*)\,\delta} > 0. \tag{2}$$

Intuitively, V_∞ increases with δ for two reasons: because the payoff of innovating increases, and because the continuation value in case of a failed innovation increases.

From (1) and (2) it follows that

$$\frac{\partial p_\infty^*}{\partial \delta} = \frac{1}{2\,\lambda}\left(\frac{1}{(1-\delta)^2} - V_\infty - \delta\frac{\partial V_\infty}{\partial \delta}\right) = \frac{1}{2\,\lambda}\left(\frac{\frac{1}{1-\delta} - \delta\, V_\infty}{1-(1-p_\infty^*)\,\delta}\right) > 0.$$

An increase in δ has three effects on p_t^*: the payoff from innovating increases, which tends to increase p_t^*; the continuation payoff from not innovating increases, which tends to decrease p_t^*; and the continuation payoff from not innovating is discounted less, which tends to decrease p_t^*. The above equations show the first effect dominates the other two, and thus p_∞^* increases with δ.

Next, I study a decision node in which the innovator has obtained and implemented the innovation but does not have the complementary asset, and in which the imitator has not imitated the innovator's innovation.

A.2. **Firm 1 has implemented the innovation but does not have the complementary asset.** As long as the imitator does not imitate the innovator, and the innovator does not obtain the complementary asset, the innovator has a market profit of $1-\alpha$ and the imitator has a profit of 0. At time T, the innovator obtains the complementary asset, which implies the imitator does not invest in R&D for $t \geq T$ (after T, imitating would only lead to competitive parity). Thus, at time T the innovator receives a discounted sum of payoffs of $\frac{1}{1-\delta}$ and the imitator obtains 0. If the imitator imitates the innovation at $t < T$, the innovator stops developing the complementary asset, the imitator receives a discounted sum of payoffs of $\frac{\alpha}{1-\delta}$, and the innovator obtains 0.[14]

Let W_t be the imitator's expected profit in period t. For $t \geq T$, the imitator does not invest in R&D, so $W_T = W_{T+1} = \ldots = 0$. For $t < T$, W_t satisfies the Bellman equation

$$W_t = \max_{q_t \in [0,1]} \left(q_t \frac{\alpha}{1-\delta} + (1-q_t)\,\delta\, W_{t+1} - \mu\, {q_t}^2\right).$$

The optimal probability of imitation at t is

$$q_t^* = \frac{1}{2\,\mu}\left(\frac{\alpha}{1-\delta} - \delta\, W_{t+1}\right). \tag{3}$$

The assumption $\mu > \frac{\alpha}{2(1-\delta)}$ guarantees that $q_t^* < 1$ for all t. Firm 2's expected profits evolve according to the difference equation

$$W_t = \delta\, W_{t+1} + \frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta} - \delta\, W_{t+1}\right)^2.$$

[14]Recall the innovator incurs in a small cost while it develops the complementary asset. Thus, if the imitator imitates the innovation before the innovator obtains the complementary asset, the innovator exits the market.

This difference equation does not have an explicit solution, but W_t can be obtained iterating backwards from $W_T = 0$. For $T-1$ and $T-2$, I obtain

$$W_{T-1} = \frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta}\right)^2,$$

$$W_{T-2} = \delta\,\frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta}\right)^2 + \frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta} - \delta\,\frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta}\right)^2\right)^2.$$

Further values of W_t are easy to obtain but are notationally cumbersome. Lemma 1 describes W_t and q_t^*'s dynamics.

Lemma 1 (Imitation dynamics)**.** *The imitator's expected profit W_t is decreasing in $t < T$ and the probability of imitation q_t^* is increasing in $t < T$.*

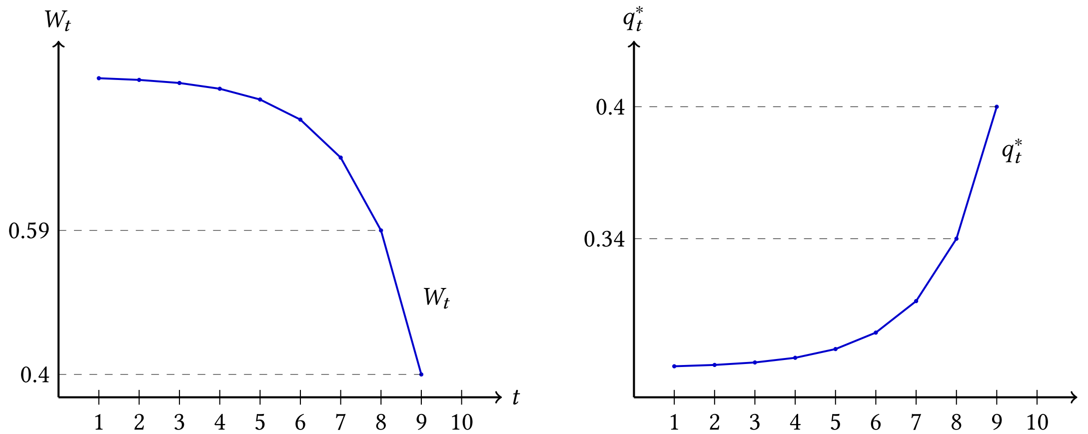
Proof. Working with the difference $W_t - W_{t-1}$ I obtain

$$\begin{aligned} W_t - W_{t-1} &= \delta\,W_{t+1} + \frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta} - \delta\,W_{t+1}\right)^2 - \left(\delta\,W_t + \frac{1}{4\,\mu}\left(\frac{\alpha}{1-\delta} - \delta\,W_t\right)^2\right), \\ &= \delta\,W_{t+1} + \frac{1}{4\,\mu}\left(\left(\frac{\alpha}{1-\delta}\right)^2 - \frac{2\,\alpha\,\delta}{1-\delta}\,W_{t+1} + \delta^2\,W_{t+1}^2\right), \\ &\quad -\delta\,W_t - \frac{1}{4\,\mu}\left(\left(\frac{\alpha}{1-\delta}\right)^2 - \frac{2\,\alpha\,\delta}{1-\delta}\,W_t + \delta^2\,W_t^2\right), \\ &= \delta\left(1 - \frac{\alpha}{2\,\mu\,(1-\delta)}\right)(W_{t+1} - W_t) + \frac{\delta^2}{4\,\mu}\left(W_{t+1}^2 - W_t^2\right). \end{aligned}$$

Given that $1 - \frac{\alpha}{2\,\mu\,(1-\delta)} > 0$, $W_{t+1} < W_t$ implies $W_t < W_{t-1}$. We know that $W_T < W_{T-1}$. Thus, W_t is decreasing for $t < T$. The result that q_t^* is increasing in t follows from (3). ■

If the imitator fails to imitate the innovator's innovation in a given period, she can try again in the next period, until the innovator obtains the complementary asset. Thus, the imitator's expected profit decreases as the deadline T approaches. Given that the continuation value of not imitating decreases with t, the imitator's incentives to invest in R&D increase with t. Figure 7 illustrates Lemma 1's results for $\alpha = 0.5$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, and $T = 10$.

A.3. **Firm 1 has innovated but has not implemented the innovation.** I consider now a decision node in which the innovator has obtained the innovation but has not implemented it. As explained in Section A.1, for $t = T$ the implementation decision is trivial, since the imitator will not invest in R&D if the innovation is implemented. For $t < T$, the implementation decision is affected by a *trade-off between short-term and long-term profitability*: implementing the innovation sooner increases product-market revenues but at the same time enables imitation by the imitator.



(A) $\alpha = 0.5$, $\delta = 0.5$, $\mu = 2.5$, $\lambda = 5$, $T = 10$ (B) $\alpha = 0.5$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, $T = 10$

FIGURE 7. Firm 2's expected profit and optimal probability of imitation ($\alpha = 0.5$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, $T = 10$). At $T = 10$, the innovator obtains the complementary asset so $W_{10} = q_{10}^* = 0$.

Let Z_t be the innovator's expected profit at t if it has implemented innovation at or before t and the imitator has not imitated it yet. For $t \geq T$, the imitator does not invest in R&D and thus $Z_t = \frac{1}{1-\delta}$. For $t < T$, Z_t satisfies the recursion

$$Z_t = (1 - q_t^*)(1 - \alpha) + (1 - q_t^*)\,\delta\, Z_{t+1}, \tag{4}$$

where q_t^* is the imitator's optimal probability of imitation, obtained in Section A.2.

If the innovator innovates in period $t < T$, she must choose the time $x \in \{t, t+1, t+2, \ldots, T\}$ at which to implement the innovation. If the innovator innovates in period t and implements the innovation in $x \geq t$, she obtains a discounted expected profit of $\delta^{x-t} Z_x$. Firm 1's implementation problem is thus to choose x to maximize $\delta^{x-t} Z_x$.

The following lemma shows the optimal implementation time for an innovation at time $t < T$ is either t or T, and characterizes the optimal implementation time as a function of parameters.

Lemma 2 (Optimal implementation of innovations)**.** *There exists a threshold $\hat{\mu}$ such that if $\mu \geq \hat{\mu}$ the innovation is implemented immediately (in the same period it is obtained), and if $\mu < \hat{\mu}$, there exists a threshold $t^* < T$ such that the innovation is implemented with delay (at time T) if it is obtained at $t \in [t^*, T)$ and is implemented immediately otherwise.*

Proof. Note that $\delta^{x-t} Z_x > \delta^{x+1-t} Z_{x+1}$ if and only if $Z_x > \delta\, Z_{x+1}$, and $\delta^{x-t} Z_x < \delta^{x+1-t} Z_{x+1}$ if and only if $Z_x < \delta\, Z_{x+1}$. Let $h_t = 1 - q_t^*$. From (4),4 it follows that

$$\begin{aligned} Z_x - \delta\, Z_{x+1} &= h_x(1-\alpha) + h_x\,\delta\, Z_{x+1} - \delta(h_{x+1}(1-\alpha) + h_{x+1}\,\delta\, Z_{x+2}), \\ &= (h_x - \delta\, h_{x+1})(1-\alpha) + \delta\,(h_x Z_{x+1} - \delta\, h_{x+1} Z_{x+2}). \end{aligned}$$

The first term on the right hand side is positive because h_t is decreasing by Lemma 1. If $Z_{x+1} - \delta\, Z_{x+2} > 0$ the second term is also positive and thus $Z_x - \delta\, Z_{x+1}$ is positive. Therefore, if $Z_{x'} - \delta\, Z_{x'+1} > 0$ at some x', it is positive for all $x < x'$. As x goes to $-\infty$, Z_x converges to a stationary value $Z_{-\infty} > 0$ and $Z_x - \delta\, Z_{x+1}$ converges to $(1-\delta)\, Z_{-\infty} > 0$. Thus, $Z_x - \delta\, Z_{x+1} > 0$ if x is sufficiently far from T.

Given these results, there are two cases: (a) if $Z_{T-1} - \delta\, Z_T \geq 0$ then $Z_x - \delta\, Z_{x+1} > 0$ for all $x < T-1$, and (b) if $Z_{T-1} - \delta\, Z_T < 0$ then there exists $t^* < T-1$ such that $Z_x - \delta\, Z_{x+1} > 0$ for $x \leq t^*$ and $Z_x - \delta\, Z_{x+1} < 0$ for $x > t^*$. In case (a), $\delta^{x-t}\, Z_x$ is decreasing in x for all $x < T$. Thus, the optimal implementation time is t for all $t < T$. In case (b), $\delta^{x-t}\, Z_x$ is decreasing in x for $x \leq t^*$ and increasing in x for $x > t^*$. Thus, it is optimal to implement an innovation in the same period it is obtained if the innovation is obtained in $t \leq t^*$, and it is optimal to implement an innovation in T if it is obtained in $t > t^*$.

We know that $Z_T = \frac{1}{1-\delta}$, and it is straightforward to obtain that $q^*_{T-1} = \frac{\alpha}{2\,\mu\,(1-\delta)}$ and $Z_{T-1} = \left(1 - q^*_{T-1}\right)\,(1 - \alpha + \delta/(1-\delta))$. Working with these expressions, we obtain that $Z_{T-1} - \delta\, Z_T \geq 0$ if and only if $\frac{(1-\alpha)\,(1-\delta)}{\delta + (1-\alpha)\,(1-\delta)} \geq \frac{\alpha}{2\,\mu\,(1-\delta)}$, and $Z_{T-1} - \delta\, Z_T < 0$ if and only if $\frac{(1-\alpha)\,(1-\delta)}{\delta + (1-\alpha)\,(1-\delta)} < \frac{\alpha}{2\,\mu\,(1-\delta)}$. Rearranging these inequalities, we obtain $\hat{\mu}$. ■

The proof of Lemma 2 shows $\delta^{x-t}\, Z_x$ is convex in x for fixed t. Thus, for any t, the optimal implementation time is either t or T. This result implies, in order to decide when to implement an innovation, we only need to compare Z_t (the expected profit from implementing the innovation immediately) and $\delta^{T-t}\, Z_T = \delta^{T-t} \frac{1}{1-\delta}$ (the expected profit from waiting until T to implement the innovation).

In the proof of Lemma 2, I show the threshold for the imitation cost parameter that determines whether implementation delays are possible is

$$\hat{\mu} = \frac{\alpha\, \left(\delta + (1-\alpha)\,(1-\delta)\right)}{2\,\mu\,(1-\alpha)\,(1-\delta)^2},$$

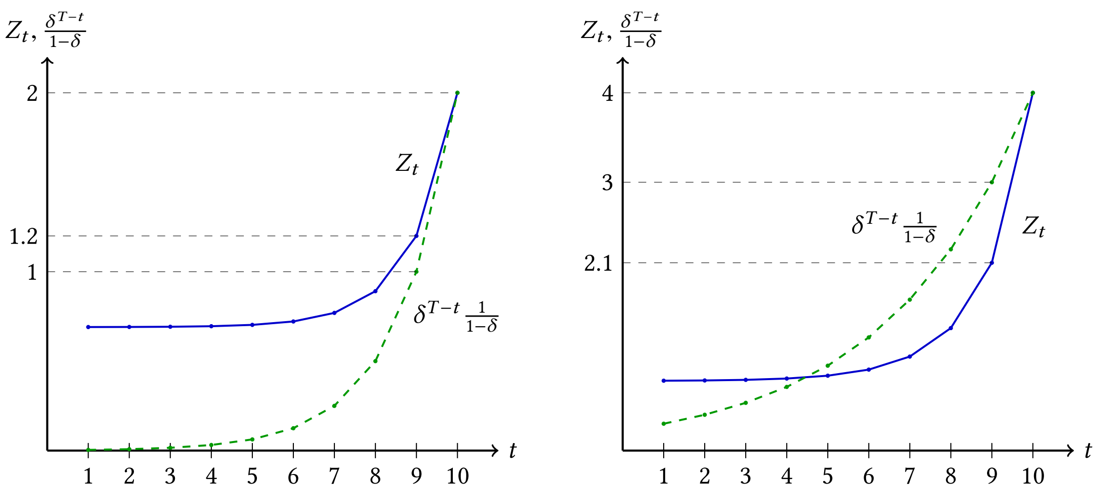
which increases with α and δ. This means that implementation delays become more likely as the imitator's initial resource advantage becomes more important or the discount factor increases.

If the imitation cost parameter μ is large, the optimal investment in imitation of the imitator is small, so the innovator's implementation trade-off is resolved in favor of gaining positive product-market revenues for a longer period of time. Thus, the innovator implements any innovation as soon as she obtains it.

For small μ, the resolution of the trade-off depends on the time left until the innovator obtains the complementary asset, and there exists a threshold $t^* < T$ such that the innovator implements the innovation immediately if she obtains before t^* and she implements it with delay if she innovates at or after t^*.

Intuitively, if t is sufficiently far from T, implementing the innovation with delay yields a low discounted payoff, and the innovator prefers to implement the innovation immediately. If t is sufficiently close to T, the prize for having both innovation and complementary asset is at hand, and the innovator chooses to implement the innovation with delay to prevent imitation.

Figure 8 illustrates the results of Lemma 2 for different values of the parameters. In Figure 8a, $Z_t \geq \delta^{T-t}\frac{1}{1-\delta}$ for all t, so it is always optimal to implement the innovation immediately. In Figure 8b, $Z_t > \delta^{T-t}\frac{1}{1-\delta}$ for $t \leq 4$ and $Z_t < \delta^{T-t}\frac{1}{1-\delta}$ for $t > 4$, so it is optimal to implement the innovation immediately if the innovation is obtained before period 4, and it is optimal to implement the innovation with delay if it is obtained afterwards.



(A) $\alpha = 0.5$, $\delta = 0.5$, $\mu = 2.5$, $\lambda = 5$, $T = 10$ (B) $\alpha = 0.5$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, $T = 10$

FIGURE 8. Comparison of payoffs with immediate (Z_t) and delayed ($\delta^{T-t}/(1-\delta)$) implementation.

Next, I study the optimal investment in R&D for nodes in which the innovator has not finished development of the complementary asset.

A.4. **Firm 1 has not innovated and does not have the complementary asset.** For $t < T$, the innovator's investment in R&D depends on the solution to the optimal implementation time studied in the previous section. Let Y_t be the expected profit from innovating at time $t < T$, which by Lemma 2 is equal to

$$Y_t = \max\left\{Z_t,\ \delta^{T-t}\,\frac{1}{1-\delta}\right\}.$$

For $t < T$, the innovator's expected profit evolves according to the following Bellman equation:

$$V_t = \max_{p_t \in [0,1]} \left(p_t\, Y_t + (1-p_t)\,\delta\, V_{t+1} - \lambda\, {p_t}^2\right).$$

The optimal probability of innovation at t is

$$p_t^* = \frac{Y_t - \delta\, V_{t+1}}{2\,\lambda}, \tag{5}$$

and the expected profit of the innovator at t follows the difference equation

$$V_t = \delta\, V_{t+1} + \frac{(Y_t - \delta\, V_{t+1})^2}{4\,\lambda}. \tag{6}$$

Lemma 3 (Innovation dynamics)**.** *Expected values Z_t, Y_t and V_t are increasing in $t < T$. Given an implementation threshold t^*, if $t > t^*$ the optimal probability of innovation p_t^* is increasing in t, and if $t \leq t^*$, p_t^* may be increasing or decreasing in t. The probability of innovation in any period $t < T$ is smaller than the probability of innovation in $t \geq T$.*

Proof. If the optimal implementation time at t is T, then $Y_t = \delta^{T-t}\frac{1}{1-\delta}$. By results in the proof of Lemma 2, the optimal implementation time at $t+1$ is also T, and thus $Y_{t+1} = \delta^{T-t-1}\frac{1}{1-\delta} = \delta^{-1}\, Y_t > Y_t$. Therefore, Y_t is increasing in t. If the optimal implementation time at t is t, then $Y_t = Z_t$. Operating, we obtain

$$\begin{aligned} Z_{t+1} - Z_t &= h_{t+1}(1-\alpha) + h_{t+1}\,\delta\, Z_{t+2} - (h_t(1-\alpha) + h_t\,\delta\, Z_{t+1}), \\ &= (h_{t+1} - h_t)(1-\alpha) + h_{t+1}\,\delta\, Z_{t+2} - h_t\,\delta\, Z_{t+1} + h_t\,\delta\, Z_{t+2} - h_t\,\delta\, Z_{t+2}, \\ &= (h_{t+1} - h_t)(1 - \alpha + \delta\, Z_{t+2}) + h_t\,\delta\,(Z_{t+2} - Z_{t+1}). \end{aligned}$$

From Lemma 1, $h_{t+1} < h_t$. This result, together with $h_t\,\delta < 1$, implies $Z_{t+1} - Z_t < Z_{t+2} - Z_{t+1}$. Thus, $Z_{t+2} - Z_{t+1} < 0$ implies $Z_{t+1} - Z_t < 0$. From Lemma 2, Z_t converges to $Z_{-\infty} > 0$ as $t \to -\infty$. Thus, $Z_{t+1} - Z_t > 0$ for all t. Otherwise, if $Z_{t+1} - Z_t < 0$ for some t, then $0 > Z_{t+1} - Z_t > Z_t - Z_{t-1} > Z_{t-1} - Z_{t-2} \ldots$ and Z_t diverges as t goes to $-\infty$. Therefore, Z_t and Y_t are increasing in t.

In Section A.1 I showed that $V_t = V_{t+1} = V_\infty$ for $t \geq T$, where V_∞ solves

$$V_\infty = \max_{p\in[0,1]} \left(p\,\frac{1}{1-\delta} + (1-p)\,\delta\, V_\infty - \lambda\, p^2 \right).$$

Given that $V_T = V_\infty$, for V_{T-1} we have

$$V_{T-1} = \max_{p\in[0,1]} \left(p\, Y_{T-1} + (1-p)\,\delta\, V_\infty - \lambda\, p^2 \right).$$

It is clear that $V_{T-1} < V_T = V_\infty$ given that $Y_{T-1} < \frac{1}{1-\delta}$. Similarly, for V_{T-2} we have

$$V_{T-2} = \max_{p\in[0,1]} \left(p\, Y_{T-2} + (1-p)\,\delta\, V_{T-1} - \lambda\, p^2 \right),$$

and $V_{T-2} < V_{T-1}$ given that $Y_{T-2} < Y_{T-1}$ and $V_{T-1} < V_T = V_\infty$. Iterating backwards, we obtain that $V_t < V_{t-1}$ for all $t < T$.

Next, I study the optimal dynamics of p_t^*. From (6), we know

$$V_{t+1} = \delta\, V_{t+2} + \frac{(Y_{t+1} - \delta\, V_{t+2})^2}{4\,\lambda},$$

from which it follows that

$$\begin{aligned}
Y_t - \delta\, V_{t+1} &= Y_t - \delta^2\, V_{t+2} - \delta \frac{(Y_{t+1} - \delta\, V_{t+2})^2}{4\,\lambda}, \\
&= Y_t - \delta^2\, V_{t+2} - \delta \frac{(Y_{t+1} - \delta\, V_{t+2})^2}{4\,\lambda} + \delta\, Y_{t+1} - \delta\, Y_{t+1}, \\
&= (Y_t - \delta\, Y_{t+1}) + \delta(Y_{t+1} - \delta\, V_{t+2}) - \delta \frac{(Y_{t+1} - \delta\, V_{t+2})^2}{4\,\lambda}.
\end{aligned}$$

If $Y_t = \delta^{T-t} \frac{1}{1-\delta}$ then $Y_{t+1} = \delta^{T-t-1} \frac{1}{1-\delta} = \delta^{-1}\, Y_t$, which implies $Y_t - \delta\, V_{t+1} < Y_{t+1} - \delta\, V_{t+2}$. Thus, $p_t^* < p_{t+1}^*$ by (5). If $Y_t = Z_t$ then the first term in the right hand side may be positive or negative, which implies $Y_t - \delta\, V_{t+1}$ may be smaller or larger than $Y_{t+1} - \delta\, V_{t+2}$.

Finally, to show $p_t^* < p_\infty^*$ for all $t < T$, note that from (5) and (6) we can write

$$V_{t+1} - V_t = V_{t+1} - \delta\, V_{t+1} - \frac{(Y_t - \delta\, V_{t+1})^2}{4\,\lambda} = (1-\delta)\, V_{t+1} - \lambda\, p_t^{*2}.$$

Given that V_t is increasing for $t < T$ and $V_T = V_\infty$, it follows that

$$p_t^* < \left(\frac{(1-\delta)\, V_{t+1}}{\lambda}\right)^2 < \left(\frac{(1-\delta)\, V_\infty}{\lambda}\right)^2$$

for $t < T$. Introducing V_∞ (obtained in Section A.1) into this expression, I obtain

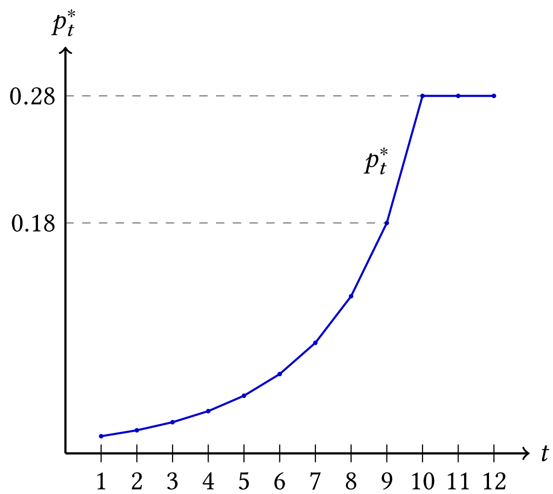
$$p_t^* < \left(\frac{(1-\delta)\, \left(2\,\lambda\,(1-\delta) + \frac{\delta}{1-\delta} - 2\, \left(\lambda^2\,(1-\delta)^2 + \lambda\,\delta\right)^{1/2}\right)}{\lambda\,\delta^2}\right)^2.$$

The result that $p_t^* < p_\infty^*$ follows because the right hand side of this inequality is always smaller than p_∞^*, obtained in Section A.1. ■

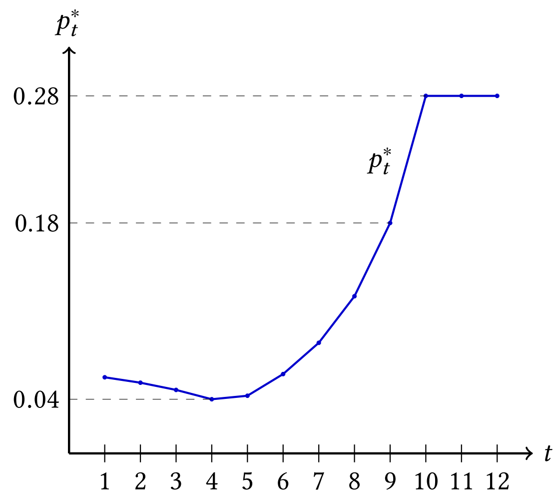
As t moves closer to T, the expected value of a successful innovation, Y_t, and the expected profit from investing in R&D, V_t, increase. By (5), the effect on the probability of innovation depends on the relative impact of changes in Y_t and $\delta\, V_{t+1}$: moving closer to T implies the payoff from a successful innovation increases, which tends to increase the innovator's investment in R&D; but the continuation payoff from failing to obtain an innovation also increases, which tends to decrease the innovator's investment. Lemma 3 shows the second effect dominates the first for some values of the parameters, in which case p_t^* may decrease with t.

Regardless of the result that p_t^* may be decreasing in t, Lemma 3 shows the probability of innovation is always larger after the innovator obtains the complementary asset, which is an intuitive result given the complementarity between the innovation and the complementary asset.

Figure 9 shows the probability of innovation for different values of the parameters. In Figure 9a, the probability is increasing until $t = 10$, and constant after that. In Figure 9b, the probability is decreasing until $t = 4$, increasing for t between 5 and 10, and constant after that. Figure 10 shows the innovator's expected profit V_t for different values of the parameters. As expected from the theoretical results, V_t is increasing until $T = 10$, and is constant thereafter.

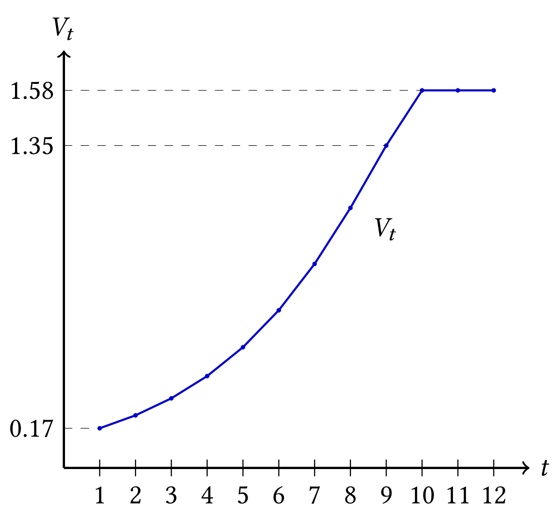


(A) $\alpha = 0.75$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, $T = 10$.

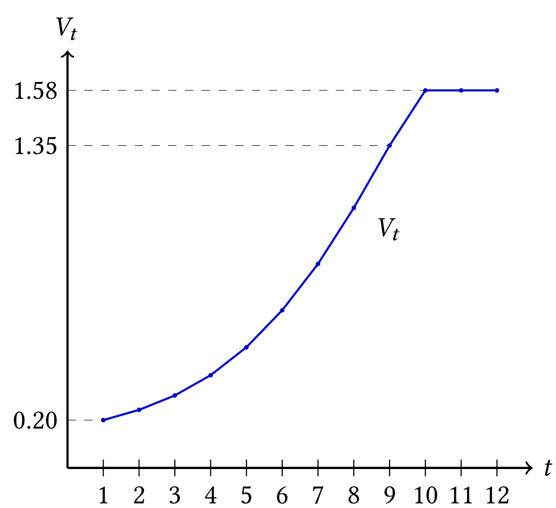


(B) $\alpha = 0.5$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, $T = 10$.

FIGURE 9. Firm 1's optimal probability of innovation.



(A) $\alpha = 0.75$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, $T = 10$.



(B) $\alpha = 0.5$, $\delta = 0.75$, $\mu = 2.5$, $\lambda = 5$, $T = 10$.

FIGURE 10. Firm 1's expected profit.

A.5. **Proof of Proposition 1.** Existence and uniqueness follow from this being a dynamic game of complete information. Other results follow from Lemmas 1, 2 and 3.

Appendix B. Solution of the model with licensing

B.1. **Proof of Proposition 2.** Working with the inequality $\delta/(1-\delta) > R^1_{T-1}$, obtained in the main text, I obtain that marketing the innovation is better than licensing if

$$\mu < \tilde{\mu} = \frac{\alpha\,(2-\alpha\,(1-2\,\delta))}{4\,(2-\alpha)\,(1-\delta)^2}.$$

The right hand side of this inequality is always smaller than $\hat{\mu}$ (given in Lemma 2) and is larger than $\frac{1}{2\,(1-\delta)}$ only if $\delta > 1/4$ and

$$\alpha > \tilde{\alpha} = \frac{2-\delta+\sqrt{\delta\,(8-7\,\delta)}}{1-2\,\delta}.$$

The result follows.

B.2. **Recursive formulation for negotiated payoffs.** In the main text, I explain that the innovator's best alternative to an agreement in $t < T-1$ is to implement the innovation in t and try to negotiate another agreement in $t+1$, and the imitator's best alternative is to try to imitate the innovation in t and, if she fails to imitate in t, try to negotiate another agreement in $t+1$. If negotiations break down, firm 2's optimal investment in R&D in period $t < T-1$ is

$$s_t^* \;=\; \underset{s_t\in[0,1]}{\operatorname{argmax}} \left(s_t\,\frac{\alpha}{1-\delta} + (1-s_t)\,\delta\,R^2_{t+1} - \mu\,s_t^2\right) \;=\; \frac{1}{2\mu}\left(\frac{\alpha}{1-\delta} - \delta\,R^2_{t+1}\right).$$

Given s_t^*, outside options are

$$\begin{aligned} O^1_t &= (1-s_t^*)\,\left(1-\alpha+\delta\,R^1_{t+1}\right), \\ O^2_t &= s_t^*\,\frac{\alpha}{1-\delta} + (1-s_t^*)\,\delta\,R^2_{t+1} - \mu\,s_t^{*2}, \end{aligned}$$

and negotiated payoffs are

$$\begin{aligned} R^1_t &= \frac{1}{2}\,O^1_t + \frac{1}{2}\left(\frac{1}{1-\delta} - O^2_t\right), \\ R^2_t &= \frac{1}{2}\,O^2_t + \frac{1}{2}\left(\frac{1}{1-\delta} - O^1_t\right). \end{aligned}$$

I obtain the values of O^1_t, O^2_t, R^1_t and R^2_t iterating backwards from R^1_{T-1} and R^2_{T-1}.

Appendix C. Solution of the model with endogenous resource development

C.1. **Proof of Proposition 3.** Proposition 3 follows from lemma 4 below, which presents additional results not included in the main text.

For concreteness, I make the dependence of T explicit by including it as an index in all endogenous variables. For example, $V_{t,T}$ and $p^*_{t,T}$ stand for firm 1's expected payoff and optimal probability of innovation at t when developing time is T. Likewise, let $t^*_T \leq T$ be the threshold period for implementing an innovation with delay (i.e., given T, if firm 1 innovates at $t \leq t^*_T$, she implements the innovation immediately; and if she innovates at $t > t^*_T$, she implements the innovation in T).

The *expected time to innovation* at time t given developing time T is

$$E_{t,T} = p^*_{t,T}\,1 + (1 - p^*_{t,T})\,p^*_{t+1,T}\,2 + (1 - p^*_{t,T})\,(1 - p^*_{t+1,T})\,p^*_{t+2,T}\,3 + \dots$$

As we saw in Section A.1, for $t \geq T$ the probability of innovation is constant and equal to p_∞, which means that $E_{t,T} = \frac{1}{p_\infty}$ for $t \geq T$. For $t < T$, the expected time to innovation can be calculated recursively from $E_{t,T} = 1 + (1 - p^*_{t,T})E_{t+1,T}$.

The *overall probability of imitation* in $\{t, t+1, \dots, T\}$ is the probability that firm 2 imitates firm 1's innovation from period t onwards. This probability is given by

$$Q_{t,T} = 1 - (1 - q^*_{t,T})\,(1 - q^*_{t+1,T})\ \dots\ (1 - q^*_{T-1,T}) \tag{7}$$

if $t \leq t^*_T$, and is equal to zero if $t > t^*_T$. Likewise, the *probability of an implementation delay* is the probability that firm 1 implements an innovation with delay. If $t \geq T$, the probability of a delay in implementation is equal to zero, since any innovation will be implemented as soon as it is obtained. If $t^*_T < t < T$, the probability is

$$D_{t,T} = 1 - (1 - p^*_{t,T})\,(1 - p^*_{t+1,T})\ \dots\ (1 - p^*_{T-1,T}),$$

since in this case there would be an implementation delay only if firm 1 innovates before T. Finally, if $t \leq t^*_T$, the probability of an implementation delay is

$$D_{t,T} = (1 - p^*_{t,T})\,(1 - p^*_{t+1,T})\ \dots\ (1 - p^*_{t^*_T,T})\,D_{t^*_T+1,T}$$

since in this case there would be an implementation delay only if firm 1 does not innovate at or before t^*_T, and innovates before T.

Given that for any t, T, equilibrium decisions depend on the difference $T - t$ (for example, the problem at $t = 4$ when $T = 6$ is equivalent to the problem at $t = 7$ when $T = 9$), it follows that $q^*_{t,T} = q^*_{t+1,T+1}$, $W_{t,T} = W_{t+1,T+1}$, $Z_{t,T} = Z_{t+1,T+1}$, $Y_{t,T} = Y_{t+1,T+1}$, $p^*_{t,T} = p^*_{t+1,T+1}$, $V_{t,T} = V_{t+1,T+1}$, $t^*_{T+1} = t^*_T + 1$, $E_{t,T} = E_{t+1,T+1}$, $Q_{t,T} = Q_{t+1,T+1}$, and $D_{t,T} = D_{t+1,T+1}$.

The following lemma shows the effect of changes in T on the equilibrium.

Lemma 4 (Effects of a change in development time). *Given $t \leq T$, the probability of imitation $q^*_{t,T}$ and expected values $Z_{t,T}$, $Y_{t,T}$ and $V_{t,T}$ are decreasing in T; and the expected imitator's profit $W_{t,T}$, implementation threshold t^*_T, and overall probability of imitation $Q_{t,T}$ are increasing in T. If $t > t^*_T + 1$, then $p^*_{t,T}$ decreases with T and the expected time to innovation $E_{t,T}$ increases with*

T. If $t \leq t^*_T + 1$, then $p^*_{t,T}$ may increase or decrease with T. The probability of an implementation delay $D_{t,T}$ decreases with T if $t \leq t^*_T + 1$, and increases with T if $t^*_T + 1 < t \leq T$.

Proof. From Lemma 1 we know that $q^*_{t,T}$ is increasing in t for fixed T, i.e., $q^*_{t+1,T} > q^*_{t,T}$. Given that $q^*_{t,T} = q^*_{t+1,T+1}$, it follows that

$$q^*_{t,T} = q^*_{t+1,T+1} > q^*_{t,T+1}.$$

Thus, $q^*_{t,T}$ is decreasing in T for fixed t. Similarly, from Lemma 1 we know that $W^*_{t,T}$ is decreasing in t for fixed T, and from Lemma 3 we know that $Z_{t,T}$, $Y_{t,T}$, and $V_{t,T}$ are increasing in t for fixed T; so $W^*_{t,T}$ is increasing and $Z_{t,T}$, $Y_{t,T}$, and $V_{t,T}$ are decreasing in T for fixed t. Given that $t^*_T = t^*_{T+1} - 1$, then $t^*_{T+1} - t^*_T = 1$ so t^*_T is increasing in T. From (7), it follows that

$$1 - Q_{t-1,T} \;=\; (1 - Q_{t,T})\,(1 - q^*_{t-1,T})$$

for $t \leq t^*_T$, which implies $Q_{t-1,T} > Q_{t,T}$. Given that $Q_{t-1,T} = Q_{t,T+1}$, it follows that $Q_{t,T+1} = Q^*_{t-1,T} > Q_{t,T}$, so $Q_{t,T}$ is increasing in T if $t \leq t^*_T$. If $t > t^*_T$, then either $t > t^*_{T+1}$, in which case $Q_{t,T} = Q_{t,T+1} = 0$ and $Q_{t,T}$ is weakly increasing in T, or $t \leq t^*_{T+1}$, in which case $Q_{t,T+1} > Q_{t,T} = 0$ and $Q_{t,T}$ is strictly increasing in T. By Lemma 3, if $t > t^*_T + 1$, then $p^*_{t-1,T} < p^*_{t,T}$, which implies $p^*_{t,T+1} < p^*_{t,T}$, so $p^*_{t,T}$ is decreasing in T. Also, given that

$$E_{t,T} - E_{t-1,T} \;=\; (1 - p^*_{t,T})E_{t+1,T} - (1 - p^*_{t-1,T})E_{t,T},$$

if $E_{t+1,T} < E_{t,T}$ and $p^*_{t,T} > p^*_{t-1,T}$, then $E_{t,T} < E_{t-1,T}$. It is straightforward to show $E_{T,T} < E_{T-1,T}$. Thus, $E_{t-1,T}$ is decreasing for $t > t^*_T + 1$, which implies $E_{t,T}$ increasing in T for $t > t^*_T + 1$. If $t \leq t^*_T + 1$, $p^*_{t,T}$ may be increasing or decreasing in T. Finally, if $t \leq t^*_T$, the probability that there is no delay in implementation is equal to the probability that the innovator innovates at of before t^*_T, which increases with T. ■

C.2. **Proof of Proposition 4.** Given that $c_T = 0$ for $T \geq 1$, the innovator will never choose a development time greater than 1. From Section A.1 we know that

$$V_{0,0} \;=\; V_{1,1} \;=\; V_\infty \;=\; \frac{2\,\lambda\,(1-\delta) + \frac{\delta}{1-\delta} - 2\,\left(\lambda^2\,(1-\delta)^2 + \lambda\,\delta\right)^{1/2}}{\delta^2},$$

and from Section A.4 we know that

$$V_{0,1} \;=\; \delta\,V_{1,1} + \frac{\left(Y_{0,1} - \delta V_{1,1}\right)^2}{4\lambda} \;=\; \delta\,V_\infty + \frac{\left(Y_{0,1} - \delta V_\infty\right)^2}{4\lambda},$$

where

$$Y_{0,1} = \max\left\{Z_{0,1}, \frac{\delta}{1-\delta}\right\} = \max\left\{\left(1 - \frac{\alpha}{2\,\mu\,(1-\delta)}\right)\left(1 - \alpha + \frac{\delta}{1-\delta}\right), \frac{\delta}{1-\delta}\right\}.$$

Firm 1 will choose $T = 0$ over $T = 1$ if

$$\Delta V = V_{0,0} - V_{0,1} \; = \; (1-\delta)\, V_\infty - \frac{\left(Y_{0,1} - \delta V_\infty\right)^2}{4\lambda} \; \geq \; c_0.$$

and will optimally choose $T = 1$ otherwise. If $\mu < \hat{\mu}$, which implies $Y_{0,1} = \frac{\delta}{1-\delta}$, then

$$\begin{aligned}\frac{\partial \Delta V}{\partial \lambda} \;&=\; (1-\delta)\,\frac{\partial V_\infty}{\partial \lambda} + \frac{\left(\frac{\delta}{1-\delta} - \delta V_\infty\right)}{4\lambda}\,\frac{\partial V_\infty}{\partial \lambda} + \frac{\left(\frac{\delta}{1-\delta} - \delta V_\infty\right)^2}{4\lambda^2}, \\ &=\; \frac{\delta + (1-\delta)^2\lambda - 2\sqrt{\lambda}\sqrt{\delta + (1-\delta)^2\lambda}}{4\lambda^2\,(\delta + (1-\delta)^2\lambda)}.\end{aligned}$$

For $\frac{\partial \Delta V}{\partial \lambda} \geq 0$, we need

$$\begin{aligned}\delta + (1-\delta)^2\lambda \;&\geq\; 2\sqrt{\lambda}\sqrt{\delta + (1-\delta)^2\lambda}, \\ \sqrt{\delta + (1-\delta)^2\lambda} \;&\geq\; 2\sqrt{\lambda}, \\ \delta + (1-\delta)^2\lambda \;&\geq\; 4\lambda, \\ \delta \;&\geq\; \left(4 - (1-\delta)^2\right)\lambda,\end{aligned}$$

which is not possible, given that $\delta < 1$ and $\lambda > 1$. Thus, $\frac{\partial \Delta V}{\partial \lambda} < 0$. Following similar steps, it is easy to show $\frac{\partial \Delta V}{\partial \lambda} < 0$ if $\mu > \hat{\mu}$, which implies $Y_{0,1} = Z_{0,1}$. The first result in the proposition follows.

For the results concerning α and μ, note that if $\mu < \hat{\mu}$, which implies $Y_{0,1} = \frac{\delta}{1-\delta}$, ΔV does not depend on α and μ. If $\mu > \hat{\mu}$, which implies $Y_{0,1} = Z_{0,1}$, on the other hand, ΔV depends on α and μ through $Z_{0,1} = \left(1 - \frac{\alpha}{2\,\mu\,(1-\delta)}\right)\left(1 - \alpha + \frac{\delta}{1-\delta}\right)$, which is decreasing in α and increasing in μ. Thus, ΔV is increasing in α and decreasing in μ.

Finally, if $\mu < \hat{\mu}$, which implies $Y_{0,1} = \frac{\delta}{1-\delta}$, then

$$\frac{\partial \Delta V}{\partial \delta} = \frac{2\sqrt{\lambda}\sqrt{\delta + (1-\delta)^2\lambda} - \delta - 2(1-\delta)\lambda}{2\delta^2\sqrt{\lambda}\sqrt{\delta + (1-\delta)^2\lambda}} \geq 0,$$

from which the result concerning δ is obtained.

Appendix D. Solution of the model with low imitation cost

D.1. **Proof of Proposition 5.** From (3), if

$$\frac{1}{2\,\mu}\left(\frac{\alpha}{1-\delta} - \delta\, W_{t+1}\right) \geq 1,$$

then $q_t^* = 1$. Given that $W_T = 0$, for $t = T - 1$ the condition becomes

$$\frac{1}{2\,\mu}\left(\frac{\alpha}{1-\delta}\right) \geq 1 \;\Leftrightarrow\; \mu \leq \frac{\alpha}{2(1-\delta)},$$

in which case $W_{T-1} = \frac{\alpha}{1-\delta} - \mu$. For $t = T - 2$, the condition is

$$\frac{1}{2\,\mu}\left(\frac{\alpha}{1-\delta} - \delta\left(\frac{\alpha}{1-\delta} - \mu\right)\right) \geq 1 \;\Leftrightarrow\; \mu \leq \frac{\alpha}{2-\delta}.$$

The same analysis applies to periods $t < T - 2$. Thus, if $\mu \leq \frac{\alpha}{2-\delta}$ then $q_t^* = 1$ for all $t < T$.

If licensing is not possible and the innovator implements the innovation at time $t < T$, then it is imitated with probability 1 and obtains a discounted payoff of zero. Thus, the innovator will implement any innovation obtained at $t < T$ in period T.

If licensing is possible, and the innovator approaches the imitator in period t to negotiate a licensing agreement, she obtains a negotiated payoff of

$$R^1 = 0 + \frac{1}{2}\left(\frac{1}{1-\delta} - \frac{\alpha}{1-\delta} + \mu\right) = \frac{1-\alpha+\mu\,(1-\delta)}{2\,(1-\delta)}.$$

The innovator will license the innovation if

$$\begin{aligned} \delta^{T-t}\frac{1}{1-\delta} &< \frac{1-\alpha+\mu\,(1-\delta)}{2\,(1-\delta)}, \\ \delta^{T-t} &< \frac{1-\alpha+\mu\,(1-\delta)}{2}, \\ t &< T - \log_\delta\left(\frac{1-\alpha+\mu\,(1-\delta)}{2}\right), \end{aligned}$$

where $\log_\delta(x)$ is the base δ logarithm of x. Given this result, the overall probability of licensing is the probability that the innovator innovates before $\tilde{t} = T - \log_\delta\left(\frac{1-\alpha+\mu\,(1-\delta)}{2}\right)$, that is $\prod_{t=0}^{\tilde{t}} p_t^*$, where

$$p_t^* = \frac{\max\left\{\frac{1-\alpha+\mu\,(1-\delta)}{2\,(1-\delta)}, \delta^{T-t}\frac{1}{1-\delta}\right\} - \delta\,V_{t+1}}{2\,\lambda}.$$

As μ increases or α decreases, $\tilde{t}$ increases and p_t^* increases for $t \in \{0, 1, \ldots \tilde{t}\}$. Thus, the overall probability of innovation increases. Finally, it is straightforward to see that

$$\lim_{\delta\to 1}\left(T - \log_\delta\left(\frac{1-\alpha+\mu\,(1-\delta)}{2}\right)\right) = -\infty.$$

Thus, $\tilde{t}$ can be made as small as wanted by making δ sufficiently large.

References

Adner, R. (2012): *The wide lens: A new strategy for innovation.* Penguin, London, UK.

Adner, R., and R. Kapoor (2010): "Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations," *Strategic Management Journal*, 31(3), 306–333.

Adner, R., L. Pólos, M. Ryall, and O. Sorenson (2009): "The Case for Formal Theory," *Academy of Management Review*, 34(2), 201–208.

Almeida Costa, L., K. Cool, and I. Dierickx (2013): "The competitive implications of the deployment of unique resources," *Strategic Management Journal*, 34(4), 445–463.

Almeida Costa, L., and I. Dierickx (2005): "The Strategic Deployment of Quality-Improving Innovations," *Journal of Business*, 78(3), 1049–1072.

Arrow, K. (1962): "Economic welfare and the allocation of resources for invention," in *The Rate and Direction of Inventive Activity: Economic and Social Factors*, pp. 609–626. Princeton University Press, Princeton, NJ.

Barney, J. B. (1986): "Strategic Factor Markets: Expectations, Luck, and Business Strategy," *Management Science*, 32(10), 1231–1241.

——— (1991): "Firm Resources and Sustained Competitive Advantage," *Journal of Management*, 17(1), 99–120.

Chatain, O. (2014): "How do strategic factor markets respond to rivalry in the product market?," *Strategic Management Journal*, 35(13), 1952–1971.

Chatain, O., and P. Zemsky (2011): "Value creation and value capture with frictions," *Strategic Management Journal*, 32(11), 1206–1231.

Chen, M. K., and B. J. Nalebuff (2006): "One-Way Essential Complements," Cowles foundation discussion paper no. 1588, Yale University, New Haven, CT.

Cohen, W. M., and D. A. Levinthal (1989): "Innovation and Learning: The Two Faces of R&D," *Economic Journal*, 99(397), 569.

——— (1990): "Absorptive Capacity: A New Perspective On Learning And Innovation," *Administrative Science Quarterly*, 35(1), 128.

Conner, K. R. (1991): "A Historical Comparison of Resource-Based Theory and Five Schools of Thought Within Industrial Organization Economics: Do We Have a New Theory of the Firm?," *Journal of Management*, 17(1), 121–154.

D'Antoni, M., and M. A. Rossi (2014): "Appropriability and incentives with complementary innovations," *Journal of Economics and Management Strategy*, 23(1), 103–124.

Denicolo, V. (2000): "Two-Stage Patent Races and Patent Policy," *RAND Journal of Economics*, 31(3), 488.

Denicolò, V., and C. Halmenschlager (2012): "Optimal patentability requirements with complementary innovations," *European Economic Review*, 56(2), 190–204.

Dierickx, I., and K. Cool (1989): "Asset Stock Accumulation and Sustainability of Competitive Advantage," *Management Science*, 35(12), 1504–1511.

Fudenberg, D., and J. Tirole (1985): "Preemption and Rent Equalization in the Adoption of New Technology," *Review of Economic Studies*, 52(3), pp. 383—-401.

Gallini, N. T. (1992): "Patent policy and costly imitation," *RAND Journal of Economics*, 23(1), 52–63.

Gilbert, R. J., and M. L. Katz (2011): "Efficient division of profits from complementary innovations," *International Journal of Industrial Organization*, 29(4), 443–454.

Gilbert, R. J., and D. M. G. Newbery (1982): "Preemptive Patenting and the Persistence of Monopoly," *American Economic Review*, 72(3), 514–526.

Grahovac, J., and D. J. Miller (2009): "Competitive advantage and performance: the impact of value creation and costliness of imitation," *Strategic Management Journal*, 30(11), 1192–1212.

Green, J. R., and S. Scotchmer (1995): "On the Division of Profit in Sequential Innovation," *RAND Journal of Economics*, 16(1), 20–33.

Katz, M. L., and C. Shapiro (1987): "R and D Rivalry with Licensing or Imitation," *American Economic Review*, 77(3), pp. 402—-420.

Lee, T., and L. L. Wilde (1980): "Market Structure and Innovation: A Reformulation," *Quarterly Journal of Economics*, 94(2), 429.

Loury, G. C. (1979): "Market Structure and Innovation," *Quarterly Journal of Economics*, 93(3), 395–410.

Mahoney, J. T., and J. R. Pandian (1992): "The resource-based view within the conversation of strategic management," *Strategic Management Journal*, 13(5), 363–380.

Makadok, R. (2001): "Toward a synthesis of the resource-based and dynamic-capability views of rent creation," *Strategic Management Journal*, 22(5), 387–401.

Makadok, R., and J. B. Barney (2001): "Strategic Factor Market Intelligence: An Application of Information Economics to Strategy Formulation and Competitor Intelligence," *Management Science*, 47(12), 1621–1638.

Ménière, Y. (2008): "Patent law and complementary innovations," *European Economic Review*, 52(7), 1125–1139.

Nelson, R. R., and S. G. Winter (1982): *An Evolutionary Theory of Economic Change*. Harvard University Press, Cambridge, MA.

O'Donoghue, T. (1998): "A Patentability Requirement for Sequential Innovation," *RAND Journal of Economics*, 29(4), 654.

Pacheco-de Almeida, G., and P. Zemsky (2007): "The Timing of Resource Development and Sustainable Competitive Advantage," *Management Science*, 53(4), 651–666.

Peteraf, M. A. (1993): "The cornerstones of competitive advantage: A resource-based view," *Strategic Management Journal*, 14(3), 179–191.

Reinganum, J. F. (1981a): "Market Structure and the Diffusion of New Technology," *Bell Journal of Economics*, 12(2), 618.

——— (1981b): "On the Diffusion of New Technology: A Game Theoretic Approach," *Review of Economic Studies*, 48(3), 395.

——— (1982): "A Dynamic Game of R and D: Patent Protection and Competitive Behavior," *Econometrica*, 50(3), 671.

Ruiz-Aliseda, F., and P. B. Zemsky (2006): "Adoption is Not Development: First Mover Advantages in the Diffusion of New Technology," INSEAD working paper, Fontainebleau, France.

Scherer, F. M. (1967): "Research and Development Resource Allocation Under Rivalry," *Quarterly Journal of Economics*, 81(3), 359.

Schumpeter, J. A. (1935): *The Theory of Economic Development: An inquiry Into Profits, Capital, Credits, Interest and the Business Cycle*. Oxford University Press, London, UK.

——— (1942): *Capitalism, Socialism and Democracy*. Harper & Brothers, New York, NY.

Scotchmer, S. (1991): "Standing on the Shoulders of Giants: Cumulative Research and the Patent Law," *Journal of Economic Perspectives*, 5(1), 29–41.

——— (1996): "Protecting early innovators: should second-generation products be patentable?," *RAND Journal of Economics*, 27(2), 322–331.

Teece, D., and G. Pisano (1994): "The dynamic capabilities of firms: An introduction," *Industrial and Corporate Change*, 3(3), 537–556.

Teece, D. J. (1986): "Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy," *Research Policy*, 15(6), 285–305.

Teece, D. J., G. Pisano, and A. Shuen (1997): "Dynamic capabilities and strategic management," *Strategic Management Journal*, 18(7), 509–533.

Wernerfelt, B. (1984): "A resource-based view of the firm," *Strategic Management Journal*, 5(2), 171–180.

Williamson, O. (1975): *Markets and Hierarchies: Analysis and Antitrust Implications*. Free Press, New York, NY.