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RESEARCH ARTICLE

ALTRUISM OR SHREWD BUSINESS? IMPLICATIONS OF TECHNOLOGY OPENNESS ON INNOVATIONS AND COMPETITION[1]

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In today's highly competitive business environment, a growing number of high-tech firms are opening their technologies. We explore the rationale behind this unusual sharing behavior in order to understand whether it is altruism or a shrewd business move. We construct an analytical model where competing firms can choose technology openness, prototype release, or technology closedness as the technology openness strategy and make subsequent innovations on the adopted technology. In contrast to literature focusing on the demand side, our study reveals a novel explanation by shedding light on two effects of supply side. First, openness generates an information effect through which it reveals technology information to the competitor. Second, openness might also lead to an access effect in which the competitor might become a "copycat" by exerting a learning effort. Our analysis suggests that a firm's openness decision depends upon the trade-off between both effects, and the interplay is moderated by the learning costs. We find that sharing technology can alleviate costly innovation competition under certain conditions. More importantly, our results reveal that openness does not necessarily translate to higher innovation and greater consumer surplus as conventional wisdom suggests. We also illustrate the robustness of the basic rationale and enrich our findings through several extended models.

Keywords: Economics of IS, technology openness, IT innovation investment, analytical modeling

Introduction

Management of intellectual capital is playing an increasing role in competition in IT and high-tech industries. Conventional wisdom suggests that protection of proprietary intellectual property (IP hereafter) is essential to keep competitors away (Bessen 2014) and contributes to product innovation (Grindley and Teece 1997). Companies protect these assets from the public and competitors through patents, trademarks, and copyrights, as they spend significant resources to develop their intellectual assets. The phrase *open-source IP* sounds

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like an oxymoron, but in recent years, an increasing number of firms are choosing to open their technology and sharing proprietary IP in highly competitive markets.

Recently, Facebook unveiled its revolutionary Virtual Reality (VR) capture system, Facebook Surround 360. Interestingly, Facebook also shares the camera's software and hardware system on GitHub.com (Cabral 2016), so any interested competitor can adopt the technology and make further innovations on it. Elon Musk, CEO of Tesla Motors, made an influential announcement in June 2014 that Tesla would open its technology and stated that other electric car manufacturers as well as the world at large would benefit from a common, rapidly evolving technology platform (Musk 2014). Shortly after that, Toyota also released a number patents for free adoption by other auto manufacturers (Toyota 2015). IBM has also embraced technology openness and recently announced two initiatives: developer Works Open (an online resource for open source code) and an academic initiative for the cloud to expand its commitment to open technology (Satell 2015). Although the base technologies would be open and free of charge, IBM can create value through innovation to design software and applications to solve customers' problems. BitPay, the largest payment processor for Bitcoin transactions, also opened their source code and a related open-source tool, allowing other developers to build blockchain software applications (Niculescu et al. 2018).

Technology openness can incentivize the developer to create additional value and generate revenue streams that firms can tax (Parker and Van Alstyne 2018; Parker et al. 2017). However, opening one's technology may also lead to some undesirable consequences, such as market cannibalization (Niculescu et al. 2018). Boudreau (2010) pointed out that sharing has the potential to build momentum behind a technology, but could leave its creator with little control or ability to appropriate value. A famous example stems from IBM's decision to sell its entire PC business to Lenovo (Spooner 2004). One of the main reasons IBM sold the business was that IBM's open architecture decision made it possible for any manufacturer to make "IBM-compatible" computers, thus making it impossible to capture long-term rents from the innovation (West 2003).

The above discussion leads us to ask why so many IT and high-tech firms share their proprietary technology with their competitors. Is this a form of altruism or a shrewd business decision? What is the underlying mechanism to gain a competitive edge? What is the consequent impact on innovation investments for different firms? To address these intriguing questions, we consider a setting with two competing firms that sell substitutable products on the market. We extend the standard Hotelling model such that competing firms are not only horizontally but also vertically differentiated. There are two stages of product development: In the beginning, both firms develop an initial proprietary technology internally, and can subsequently make investments to further improve their technology through innovation activities. As the technology openness decision is a long-term strategic decision, firms will make the decisions before they even fully realize the initial value of their technology. If a firm chooses an openness strategy, the competitor can decide whether or not to adopt that shared technology. However, translating a competitor's IP to a firm's own setting requires significant effort (Knowledge@Wharton 2014), hence there is a learning cost associated with this knowledge transfer. The learning cost varies based on different industries and companies. Our key results help to provide insights as to why so many IT and high-technology firms are willing to share their proprietary intellectual property. In addition to the technology openness and technology closedness options, we also consider the common strategy of prototype release, in which the firm can achieve certain aspects of technology openness by disclosing the initial value of their technology to the competitor.

Existing literature has primarily focused on network effects from the demand side (i.e., products and services that become more valuable to each user when more users adopt the products) to explain the motivation of technology openness strategies (Parker and Van Alstyne 2018, Niculescu et al. 2018). In contrast, our study complements the existing literature by focusing on the supply side and reveals a novel explanation for why firms are willing to disclose their proprietary technologies even in the absence of network effects. Essentially, there are two consequences that result from the decision of technology openness. On the one hand, technology openness leads to information disclosure (*information effect*). The competitor will become aware of the other firm's initial technology value and the extensibility of that technology regardless of whether it decides to adopt the opened technology or not. We show that this information effect will benefit the firm that shares the technology or releases the prototype (prototype release only reveals the initial technology value), because it can reduce costly innovation competition. On the other hand, opening one's technology might contribute to technology access (*access effect*). That is, the competitor has the opportunity to reproduce the product by acquiring the shared technology or to mimic the prototype under prototype release. The decision regarding technology openness critically depends on the trade-off between the information effect and access effect. The interplay between these two effects is moderated by the magnitudes of the learning costs and other factors. In particular, information effect always occurs along with technology openness and prototype release, while access effect may or may not be activated, or partially activated, depending on various competitive environments. Chiefly, we find that when the learning cost of acquiring alternative technology is low, technology openness will activate the access effect, yielding negative consequences for the firm that chooses openness. However, when the learning cost is substantial, the access effect is deactivated, and opening technology can benefit the firm by deterring costly innovation competition most effectively.

The main intuition driving the advantage of information effect from technology openness is as follows. When technology is closed, firms invest heavily in innovation in the face of uncertainty about a competitor's technology level. Further, echoing results from Grahovac et al. (2015), the benefit of these investments will be competed away during the price competition stage, so opening one's technology can effectively deter inefficient and costly innovation competition. In essence, technology openness under such competitive environments can be regarded as "aposematic coloration" to deter the competitor's excessive innovation generated from information opaqueness. This is consistent with the speculation of the trade press as Satell (2015) commented,

> Perhaps most importantly, IBM's commitment to open technologies is not wide-eyed altruism, but a clear-eyed business strategy. For example Watson, its advanced artificial intelligence platform, is highly dependent on open source technology. However, while everybody can access those same open resources, only IBM can do Watson.

This intuition is further supported by Karl Ulrich (Knowledge@Wharton 2014), who said "I don't believe Tesla is giving up much of substance here. Their patents most likely did not actually protect against others creating similar vehicles." According to the trade magazine (Loveday 2014), Tesla opened 249 different patents related to the electrical vehicle in 2014. Out of these 249 patents, 104 are regarding the battery system. It has also been pointed out that Tesla's battery patents are likely of no value to any other automaker, which is consistent with the observation that Detroit's Big Three (i.e., General Motors, Ford, and Chrysler) show little to no interest in these Tesla patents (Loveday 2014). The above examples clearly illustrate that Tesla successfully signaled the value of their technology to these competitors as they researched the technology carefully but decided not to adopt the shared intellectual properties (i.e., information effect). Our research clarifies the above arguments by studying the issue formally, and complements the existing literature on openness by focusing on the driver of openness from the supply side and the perspective of innovation.

More importantly, in contrast to the popular notion that opening technology can yield higher levels of innovation, and subsequently increase consumer surplus, we find that this claim is not always true. Specifically, we illustrate that technology openness can actually hinder innovation activities and hurt consumer surplus when certain conditions are met. Our findings resonate with the recent leading article in the *Harvard Business Review*, in which Wessel (2018) points out that high-tech firms can use their strength to vanquish potential competitors. Consequently, leading firms can increase profits without much innovation investment, which in turn hurts consumers. Our analysis reveals that a firm's technology openness decision does not incentivize additional innovation but serves as a shrewd business decision to drive away market competitions and might ultimately hurt consumers. Our results not only provide testable empirical questions for researchers in this area but also serve as a cautionary note to policymakers that technology openness may create some undesirable outcomes.

The rest of the paper is organized as follows: In the next section, we review the related literature and position our study with respect to it. The following two sections describe and analyze the model. We then investigate the firm's technology openness decision and its subsequent impact on innovation and consumer surplus. We consider three extensions of our model to illustrate the robustness of our findings. We conclude with managerial implications and suggestions for future research.

Literature Review

The current study draws from three distinct streams of literature, but some crucial features also deviate from the existing literature in each stream. The key contributions of our study are to understand when and why a technology firm will share its proprietary technology in a competitive environment and determine the implication of this decision on innovations.

Information Sharing

Our research intersects with the information sharing literature, specifically horizontal information sharing between competitors. In general, studies in this stream focus mainly on whether competing firms are willing to share demand or cost information with each other. Chen (2003) provides a comprehensive review of related economics papers. It has been shown that the horizontal information sharing decision between competitors depends on competition type (i.e., Cournot or Bertrand), information type (i.e., private or common parameter), and product type (i.e., substitutes or complements). Shamir and Shin (2016) find that an incumbent retailer is able to share its private forecast information credibly if and only if it shares this information within both its own supply chain and the competing supply chain. Ha et al. (2017) analyze the information sharing decisions in competing supply chains. The authors find that information sharing in one supply chain will trigger a competitive reaction from the other supply chain.

There are three crucial differences between our study and those in the information sharing literature. First, the firms in the information sharing literature are able to observe the competitor's type, but do not have the capability to acquire the opponent's proprietary technology. In our setting, if a firm decides to open its technology, it not only reveals private information, but also offers the opportunity for the competitor to adopt it. Further, the private information (i.e., technology) that each firm possesses can be endogenously improved by innovation investment. Second, in contrast to previous literature mainly focusing on the one dimensional information sharing, our model explicitly considers the endogenous decisions (prototype release and technology openness) on two dimensional information sharing (i.e., initial value and extensibility of technology). Third, previous literature typically models only one stage game after information sharing, which are usually quantity or pricing decisions. While we model two-stage competition after the sharing and learning action, and identify some negative consequences associated with technology openness. That is, technology openness may reduce firms' innovation activities.[2]

Innovation

Green and Scotchmer (1995) show that in markets with sequential innovation, broadening the first innovator's patent protection and/or permitting cooperative agreements between the incumbent innovator and later innovators can mitigate the profit erosion of the initial innovator. Bessen and Maskin (2009) illustrate that society and inventors may be better off without patent protection under sequential innovation, where an inventor's prospective profit may actually be enhanced by competition and imitation. Our model overlaps with the sequential innovation literature because the value of final products in our setting stems not only from the initial technology but also from the subsequent innovation activity.

There is another stream of literature considering IT innovation and investment explicitly. Clemons and Gu (2003) develop a general framework to evaluate contingent IT investment by incorporating the innovative applications of IT. Kleis et al. (2012) examine the contribution of IT to innovation production empirically. They find that a 10% increase in IT input is associated with a 1.7% increase in innovation output, which demonstrates the value of IT investment. Recently, Anderson et al. (2014) study the level of platform innovation when the platform exhibits two-sided network externalities. The authors show that heavy innovation in the core performance of a platform does not always yield a higher profit, because it may require a higher investment for developers to participate. Xin and Choudhary (2018) consider a setting where the amount of cost reduction depends on the level of IT investment, and the outcome of the innovation investment is uncertain. They find that implementation uncertainty actually leads to higher profit because the productivity gains are competed away in the absence of uncertainty. The focus of this stream literature is on the value of IT innovation; however, they do not take technology openness into consideration. In this research, we analytically demonstrate how technology openness can affect subsequent innovation activities.

IP Licensing and Technology Openness

Our study is also closely related to the literature on IP licensing and emerging literature on IP openness. Existing IP licensing and management literature has focused mainly on how firms can leverage IP rights to set the barrier or deter the entry in the competitive settings (Granstrand 1999). One of the key differences between the current work and traditional IP licensing literature (Reitzig 2004) is that in the open technology context, the IP owner now allows the licensee to use the technology free of charge.

Recent literature has looked into IP openness issues from different perspectives. Using a dataset of handheld computing systems, Boudreau (2010) empirically shows that granting access to a platform and opening up markets for complementary components generate a higher rate of device development compared to giving up some control over the platform. Hu et al. (2017) study technology openness from an operations perspective, where the authors consider the interplay between the supplier and competing manufacturers. They find that manufacturers can incentivize supplier investment in components by opening their technology. The objective of the existing research in this stream is to understand how the openness of a platform/technology can influence the complementary market and upstream behaviors. The focus of the current study is to investigate why firms share their technology in a

[2] We have also conducted an additional literature review on the existing studies on information sharing, which is available in Appendix A.

competitive environment and the corresponding internal innovation activities, which is distinct from the studies mentioned above.

There are also a number of papers that specifically address the technology openness decision facing IT and high-tech firms by considering network effects. Parker and Van Alstyne (2018) analyze open innovation and illustrate how a platform can optimize its openness and the duration of third-party developer IP rights to leverage downstream innovation and consider developer and platform competition in Parker et al. (2017). Recently, Niculescu et al. (2018) develop an analytical model to investigate the decision facing online platforms regarding sharing IP. The intuition behind their results lies in the trade-off between the cannibalization effects and the additional value from network effects on the consumer side. In contrast to the aforementioned studies, we focus on the supply side and illustrate that, even in the absence of network effects, the firms still have strong motivation to open their technology as a means to mitigate costly innovation competition.

Model Setting

Consider a setting where two competing firms are developing and selling substitutable products. Initially, the two firms possess initial proprietary technologies, and later both can make investments to further improve their technologies through innovation activities. Before the innovation investment, each firm can choose one of three technology release strategies: (1) technology openness, (2) prototype release,[3] or (3) technology closedness. In many software and high-tech industries, translating a competitor's coding or/and technology to its own coding or/and engineering documentation requires an intensive effort (Knowledge@Wharton 2014), which is captured by the learning cost in our model. Thus, if one firm chooses technology openness, the competing firm can adopt the shared technology free of charge, but it must incur a learning cost to absorb that technology (Cohen and Levinthal 1990). If one firm decides to release the prototype, although the competitor does not have access to the technology underlying the product, the competitor can still become a "copycat" by mimicking the prototype and incurring a mimicking cost.

We employ the Hotelling model to characterize the competition between the firms. We assume that two firms (1 and 2) are situated at locations 0 and 1 on a line with unit length. Consumers are uniformly distributed along the line, and each demands one unit of product. A consumer's utility for each product is the value that the consumer derives from the consumption subtracting the price and the disutility from the mismatch between the firm's and the consumer's locations. The consumer compares two final products and chooses the one with higher utility. The utilities for the consumer located at x from purchasing two firms' products are

$$U_1 = v_1 - tx - p_1 \text{ and } U_2 = v_2 - t(1-x) - p_2$$

where v_i is the final value of firm i's product on the market, t is the unit mismatch cost, and p_i is the price of firm i's product (i = 1, 2). Essentially, t captures the level of horizontal differentiation between the competing firms and also measures the intensity of competition (Villas-Boas and Schmidt-Nohr 1999; Xin and Choudhary 2018), where a smaller value of t implies a lower level of differentiation and higher competition intensity. In general, many factors, such as degree of loyalty or shopping habits (Lafley and Martin 2017), lead particular classes of consumers to prefer one firm to another, even with similar functionalities generated by competing products. The mismatch cost tx or $t(1-x)$ captures such consumer heterogeneity.

Following Green and Scotchmer (1995), we assume that $v_i = v_{i0} + \theta_i e_i$, where v_{i0} represents the initial value of firm i's technology, and $\theta_i e_i$ indicates the additional utility from firm i's innovation investment. Specifically, e_i is the magnitude of the innovation whose cost is ke_i^2. The convex innovation cost function is well established in the literature for innovation investment (Yin et al. 2010), reflecting the fact that the marginal return from investment decreases.[4] The parameter θ_i captures the extensibility of firm i's technology. Essentially, extensibility represents the ability to extend or stretch the functionality of the current technology or source code. If the technology is designed in a way that makes extensions easy, the value of θ_i is higher; otherwise this value is lower. We retain the common assumption that v_{i0} is sufficiently large to ensure a fully covered market. There are two possible types of each firm's initial value of technology *ex ante*, that is, $v_{i0} = v_H$ with probability α and $v_{i0} = v_L$ with probability $1 - \alpha$, where $v_L < v_H$ and $a \in (0, 1)$. The extensibility of technology also follows a discrete distribution, where $\theta_i = 1$ with probability γ and $\theta_i = \theta$ with probability $1 - \gamma$, where $\theta,\ \gamma \in (0, 1)$. The discrete distributions allow us to capture the initial value and extensibility of technology parsimoniously. Here we

[3]We thank the anonymous associate editor and reviewer who suggested this line of investigation.

[4]In the base model, we assume that the two firms have the same cost parameter k to improve technology. We also verify that the insights from the base model are robust when firms have different cost parameter k and cannot observe their competitor's innovation cost.

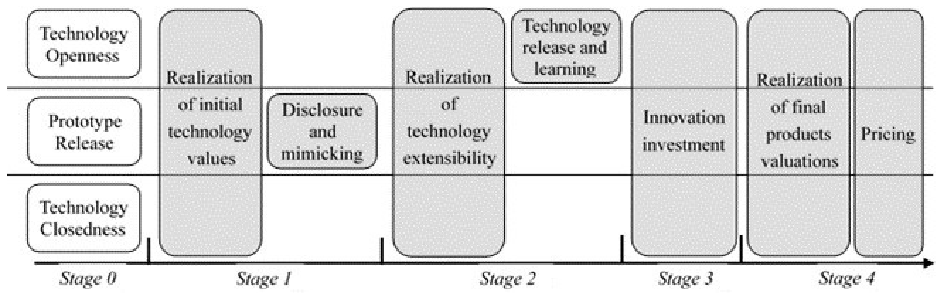

Figure 1. Sequence of Events

assume that the initial value of the technology and its extensibility are independent, given the fact that the initial value and the extensibility are not necessarily dependent on each other. For example, Sega Dreamcast was Sega's last video game console system. The gaming community showed great enthusiasm when the prototype was released, but the system was ultimately a commercial failure. Critics have cited the lack of a second analog stick or third party support as major flaws (Anderson 2016). Clearly, Dreamcast had great initial technology value, but the technology extensibility on the system was low. For the completeness of the study, we have further numerically verified that our qualitative insights are robust even when the initial value of technology and its extensibility are correlated.[5]

The timeline of our model is provided in Figure 1. We create separate timelines for different release strategies: technology openness, prototype release, and technology closedness.

In Stage 0 (Openness Commitment Stage), each firm chooses a technology release strategy simultaneously: technology openness (O), prototype release (P) or technology closedness (C). If the firm chooses technology openness, then the competing firm will be aware of both the initial value (i.e., v_{i0}) as well as the extensibility of the technology (i.e., θ_i) once they are realized in the later stages. However, when the firm only releases the prototype, the competing firm does not have the ability to assess the technology extensibility, since she cannot evaluate the source code or analyze the underlying technology empowering the prototype. As a result, if the firm chooses prototype release, the competing firm will only be aware of the initial value of her technology but not the extensibility of that technology. If the firm chooses technology closedness, the competing firm will be aware of neither the initial value nor the extensibility of her technology. In the base model, we concentrate on the scenario where the decision is made before the realization of the firm's initial technology value and its extensibility, highlighting the fact that technology openness commitment is a long-term strategy (Niculescu et al. 2018), which typically occurs before the firm fully develops or realizes how the market accepts its technology. For example, Tesla plans to open their technology on the vehicle security software for self-driving cars (Lambert 2018), which is a few years ahead of the full commercialization of self-driving cars. In an extension, we analyze an alternative timing structure where the openness decision is made after the realization of technology types.[6]

In Stage 1 (Prototype Mimicking Stage), initial technology values are realized to the firms themselves. If one firm makes the prototype release commitment in the previous stage and reveals the prototype accordingly, then the competing firm will not only realize her value but also can exert a mimicking cost f_P to become a copycat by imitating the released prototype. It's worthwhile to point out that the realizations of uncertainties are sequential. The uncertainty of the initial technology value is realized first (in Stage 1) because the initial value of the basic technology framework is determined when the prototype is finished (even if the firm chooses not to release the prototype). Then, engineers will gather feedback on their prototypes either internally or publicly to gauge the potential of their technology on innovation. As a result, the uncertainty of the technology extensibility will be realized later (in Stage 2). If one firm chooses to become a copycat, she will also realize her own technology extensibility in Stage 2 because she cannot observe the technology underlying the released prototype.

[5]The analysis is available upon request.

[6]We thank the anonymous review team for providing the constructive comments that lead to this alternative timing structure.

In Stage 2 (Technology Learning Stage), both firms realize the extensibility of their technologies.[7] If technology openness is committed in Stage 0 by one of the firms, the other firm has the option (but not necessarily) to adopt that shared technology at this stage. Because translating a competitor's source code or/and technology to her own coding or/and engineering documentation requires significant resources and intensive efforts (Knowledge@Wharton 2014), the firm that adopts the shared technology incurs a positive learning cost f_O. Note that both prototype mimicking and technology learning are observable to the competitors.[8]

In Stage 3 (Innovation Investment Stage), firms make innovation investment decisions e_i to further improve their adopted technologies. That is, firms can leverage feedback from internal testing or response to the prototype release to determine its limits, then push those limits by refining the design of the product during this stage. If both firms choose the closedness strategy initially, then they can only make innovation improvements on their own technologies.

In Stage 4 (Pricing Stage), both firms release their final products to the market, at which point they can observe the competitor's final product value and set the price p_i for their own products correspondingly. The consumers then purchase the product that provides higher utility.

There are several key features embedded in our modeling described above. To begin with, similar to that of Ferreira and Thisse (1996), our modeling technique captures both horizontal and vertical differentiation between products. Information and high-tech products typically exhibit both horizontal and vertical differentiation. Further, we introduce two-dimensional information structure of the firm's technology to differentiate between prototype release and technology openness. Although the initial value of technology can be disclosed through prototype release, the extensibility of the underlying technology can only be disclosed through a technology openness commitment. Finally, we characterize the costly technology transfer and prototype mimicking process through the learning and mimicking cost parsimoniously. To ensure the concavity of objective function and exclude the unrealistic case that innovation can be arbitrarily high, we assume that the cost parameter is not too small (i.e., $k > 1/(6t)$). Consistent with the existing literature (Parker and Van Alstyne 2018), we normalize the marginal costs to be zero. It can be readily shown that as long as both firms have similar marginal costs, our main insights still prevail qualitatively. We summarize the notations used in this study in Table 1.

[7] In the base model, we assume that the initial value is more important than the extensibility. This suggests that it is more beneficial for the firm with initial technology value v_L and extensibility 1 to learn from the competing firm with v_H and θ if the learning cost is zero. In Appendix B, we have relaxed the assumption and find this will not influence the qualitative insights.

[8] We have also shown that our insights are robust when the learning behavior is unobservable and the learning cost is asymmetric between firms.

Mimicking, Learning, Innovation and Pricing

Using backward induction, we first analyze the optimal pricing decisions in Stage 4, then characterize the firms' innovation investment decisions in Stage 3. We subsequently study the firms' technology learning and prototype mimicking decision in Stages 2, and 1, respectively.

Pricing Decision

In the final stage of the game, two firms have completed their innovation improvements and products have been finalized. We can characterize the market share for each firm by the location $\tilde{x}$ where consumers are indifferent between two firm's products. The point $\tilde{x}$ is denoted as follows:

$$\tilde{x} = \frac{v_1 - v_2 + p_2 - p_1 + t}{2t}$$

Each firm chooses the price maximizing its profit with the constraint $0 \leq \tilde{x} \leq 1$:

$$\max_{p_1} \pi_1 = p_1 \tilde{x} \text{ and } \max_{p_2} \pi_2 = p_2 (1 - \tilde{x})$$

We focus on the more interesting case where both firms have positive market share, and we summarize the equilibrium prices in the following Proposition 1.

PROPOSITION 1. *After the technology innovation, the equilibrium prices of final products are*

$$p_1 = t + \frac{v_1 - v_2}{3} \textit{ and } p_2 = t - \frac{v_1 - v_2}{3}$$

The indifferent consumer is situated at $\tilde{x} = \frac{1}{2} + \frac{v_1 - v_2}{6t}$ *, and the profits for two firms are, respectively,*

$$\pi_1^* = \frac{(v_1 - v_2 + 3t)^2}{18t} \textit{ and } \pi_2^* = \frac{(v_2 - v_1 + 3t)^2}{18t}$$

Table 1. Parameters and Decision Variables

Notation	Definition
x	Consumer's location, x is uniformly distributed over [0, 1].
U_i	Consumer utility from consumption of firm i's product, $i = 1, 2$.
v_i	The final value of firm i's product on the market, $i = 1, 2$.
p_i	The price of firm i's product, $i = 1, 2$.
t	The unit mismatch cost.
v_{i0}	The initial value of firm i's technology, $v_{i0} = v_H$ or $v_{i0} = v_L$, and $v_L < v_H$, $i = 1, 2$.
α	The probability that $v_{i0} = v_H$, and the probability that $v_{i0} = v_L$ is $1 - \alpha$, $\alpha \in (0, 1)$.
θ_i	The extensibility of firm i's technology, $\theta_i = 1$ or $\theta_i = \theta$, $\theta \in (0, 1)$, $i = 1, 2$.
γ	The probability that $\theta_i = 1$, and the probability that $\theta_i = \theta$ is $1 - \gamma$, $\gamma \in (0, 1)$.
e_i	The innovation level of firm i, $i = 1, 2$.
k	The innovation cost parameter, the disutility (investment cost) of innovation level e_i is ke_i^2.
f_O	The learning cost when the firm adopts the competitor's technology.
f_P	The mimicking cost when the firm mimics the competitor's prototype.
$\tilde{x}$	The location of the indifferent consumer between two firms.
I_i	The indicator function, $I_i = 1$ or 0, $i = 1, 2$.
π_i	The profit of firm i, $i = 1, 2$.

Table 2. Technology Openness Strategy Profiles

		Firm 2		
		Technology Openness	**Prototype Release**	**Technology Closedness**
Firm 1	**Technology Openness**	{O, O}	{O, P}	{O, C}
	Prototype Release	{P, O}	{P, P}	{P, C}
	Technology Closedness	{C, O}	{C, P}	{C, C}

All proofs, unless otherwise stated, are provided in Appendix B. Proposition 1 suggests that the equilibrium prices are pinned down by the difference between two products' final values. The firm with the higher product value can charge a price premium and obtain a greater profit than the firm with the lower value. Further, as horizontal differentiation increases (i.e., t increases), both firms compete less strenuously for the same consumer.

Innovation Investment Decision

Since each firm has three options regarding the technology openness strategy, there are nine possible equilibrium profiles as illustrated in Table 2. The first (second) argument at each strategy profile is firm 1's (2's) technology openness decision.

Note that the profiles {O, O}, {P, P} and {C, C} are the cases where two firms choose the same technology openness strategy (i.e., symmetric strategies), and the other six profiles represent the asymmetric cases where two firms choose different strategies. Next we analyze the firms' innovation decisions under symmetric strategies in detail. Due to the page limit, we leave the analysis and discussion of asymmetric strategies in Appendix B.

Scenario {O, O}

Given that both firms commit to open their technology, the initial value and extensibility of firm *i's* technology become observable to firm *j* before the innovation stage, and firm *j* has the option of adopting firm *i*'s technology, realizing the same initial value and extensibility for subsequent innovation (i, j = 1, 2; $i \neq j$). Firms may choose to insist on their own technology without adopting the competitor's. For exposition, we present the results in two sub-cases based on whether the firms are symmetric in terms of initial value and extensibility during the innovation stage.

Case 1: Symmetric firms. When two firms are symmetric at the beginning of the innovation stage, they share the same initial value and extensibility of technology, i.e., $v_{i0} = v_{j0}$ and $\theta_i = \theta_j$, which are observable to the competitors. There are two possibilities leading to symmetric firms: (1) the realizations of initial value and extensibility are the same for both firms' technologies, and thus no technology learning occurs; (2) the realizations of initial value or extensibility are different, and the firm with the low initial value or low extensibility (or both) chooses to adopt the advanced technology to realize high initial value or high extensibility (or both). Under {O, O}, there are six possible scenarios in which the inferior firm can learn from the competitor. Symmetric firms are facing the following problems to determine the innovation level, where superscript *OO* represents the scenario in which both firms open their technologies.

$$\max_{e_i} \pi_i^{OO}(e_i) = \frac{(\theta_i e_i - \theta_j e_j + 3t)^2}{18t}$$
$$-ke_i^2 - I_i f_O(\theta_i = \theta_j; i, j = 1,2; i \neq j)$$

The indicator function I_i=1 if firm *i* adopts *j*'s technology and I_i =0 otherwise. The equilibrium innovation decisions are obtained at the intersection of the best response functions of two firms. We summarize the results in the following lemma.

LEMMA 1. *Under {O, O}, when two firms are symmetric at the beginning of the innovation investment stage, the equilibrium innovation level of firm i is* $e_i^{OO} = \frac{\theta_i}{6k}(i = 1,2)$.

Lemma 1 shows that when both firms choose technology openness and realize the same initial value and extensibility, or when the firm with the inferior one adopts the advanced one, firms will invest the same amount and split the market equally (i.e., $\tilde{x}$ = 1/2). Interestingly, if neither firm makes an investment on innovation, they actually gain the greatest profits with equal market share. However, because of the dynamics similar to Prisoner's Dilemma, both firms make positive investments in equilibrium, which squeezes the profits since the benefits derived from their innovation investments get competed away at the final market.

Case 2: Asymmetric firms. In this case, firms have different initial values or different extensibility of technology or both and technology learning does not occur. The following lemma presents the equilibrium innovation decisions of the firms.

LEMMA 2. *Under {O, O}, when two firms are asymmetric at the beginning of the innovation investment stage, the equilibrium innovation level of firm i is* $e_i^{OO} = \frac{\theta_i(18kt - 2\theta_j^2)}{6k(18kt - \theta_i^2 - \theta_j^2)} + \frac{\theta_i(v_{i0} - v_{j0})}{18kt - \theta_i^2 - \theta_j^2}(i, j = 1,2; i \neq j)$.

Lemma 2 shows that under {O, O}, when both firms insist on adopting their own technology and have the same extensibility, the firm with higher initial value invests more aggressively than the firm of lower value does, leading to a greater market share and higher profit. Similarly, the firm with high extensibility invests more and takes a larger market proportion than the firm with low extensibility when firms realize the same initial value. Recall that the initial value is more important than extensibility in terms of its impact on the final product. Consequently, we can show that the firm with v_H and θ makes a higher innovation investment and obtains a greater market share than the firm with v_L and 1.

Scenario {P, P}

If both firms choose to release their prototypes, they can observe each other's initial technology value through the prototypes. Further, firm *j* has the opportunity to become the copycat by mimicking firm *i*'s prototype and produce a knockoff with similar initial value (i, j = 1, 2; $i \neq j$). We explore the innovation equilibrium of firms based on whether two firms have the same initial value.

Case 1: The Same Initial Technology Value. There are two possibilities leading to the same initial technology value of firms at the beginning of innovation stage. The first one is that two firms realize the same initial value, and thus no prototype mimicking occurs. The second one is that the firm with low initial value obtains the high value through prototype mimicking when firms realize different initial values. Further, the prototype mimicking behavior is observed by the competitor, but both firms still need to conjecture the other's technology extensibility. As a result, the innovation problems can be formulated as follows, where superscript *PP* represents the scenario in which both firms reveal prototypes. The indicator function I_i = 1 if firm *i* mimics *j*'s prototype and I_i = 0 otherwise.

$$\max_{e_i} \pi_i^{PP}(e_i) = \frac{E_{\theta_j}\left[\left(\theta_i e_i - \theta_j e_j + 3t\right)^2\right]}{18t} - ke_i^2 - I_i f_P \left(i, j = 1, 2; i \neq j\right)$$

Lemma 3 describes the equilibrium innovation levels under {P, P} with the same initial technology value.

LEMMA 3. *Under {P, P}, when firms have the same initial technology value, the equilibrium innovation level of firm i is* $e_i^{PP} = \frac{3t\theta_i}{\left(18kt-\theta_i^2\right)(1+\mu)}$, *where* $\mu = E_{\theta_i}\left(\frac{\theta_i^2}{18kt-\theta_i^2}\right)$ *and* $i = 1, 2$.

Compared with profile {O, O} where firms become symmetric after technology learning, Lemma 3 indicates that under {P, P}, even with the same initial value after prototype mimicking, firms do not necessarily invest the same on innovation. The innovation level is driven by the realization of one's own technology extensibility, since the other's remains uncertain in this case.

Case 2: Different Initial Technology Values. When firms have different initial technology values but prototype mimicking does not occur, the following lemma shows the innovation equilibrium.

LEMMA 4. *Under {P, P}, when firms have different initial technology values and no prototype mimicking occurs, the equilibrium innovation level of firm i is* $e_i^{PP} = \frac{\theta_i}{18kt-\theta_i^2}\left(\frac{3t}{1+\mu} + \frac{v_{i0}-v_{j0}}{1-\mu}\right)(i = 1, 2)$.

Lemma 4 suggests that under {P, P}, when both firms innovate on their own initial values, given the other dimension of endowment (either v_{i0} or θ_i) is the same, the firm with high endowment always invests more aggressively than the low firm does, which is consistent with the firms' behavior under {O, O}.

Scenario {C, C}

When both firms choose technology closedness, they have to make innovation investments on their own technologies, conjecturing on the competitor's two dimensional uncertainties (i.e., both initial values and extensibility of technology) and corresponding behavior. As a result, the problems can be formulated as follows, where superscript CC represents the closedness strategy for both firms.

$$\max_{e_i} \pi_i^{CC} = \frac{E_{v_{j0},\theta_j}\left[\left(v_{i0} - v_{j0} + \theta_i e_i - \theta_j e_j + 3t\right)^2\right]}{18t} - ke_i^2 \left(i, j = 1, 2; i \neq j\right)$$

Lemma 5 presents the innovation investment equilibrium and subscript H (L) represents the firm with initial technology value v_H (v_L).

LEMMA 5. *Under {C, C}, the innovation levels for firm i with high and low initial technology values are*

$$\begin{cases} e_{iH}^{CC} = \frac{\theta_i}{18kt-\theta_i^2}\left(\frac{3t}{1+\mu} + (1-\alpha)(v_H - v_L)\right) \\ e_{iL}^{CC} = \frac{\theta_i}{18kt-\theta_i^2}\left(\frac{3t}{1+\mu} - \alpha(v_H - v_L)\right) \end{cases} (i = 1, 2),$$

respectively.

Similar to the results under {O, O} and {P, P}, the firm with higher endowment (either v_{i0} or θ_i) makes a greater investment on innovation than the firm with the lower one does. Specifically, under {C, C} we can further show that firm i invests more as α decreases. Recall that α is the probability of realizing a high initial technology value. The intuition of this result is that for firm i, with a smaller α, the probability of facing a high initial value competitor becomes lower. Consequently, the potential gain from a high innovation investment becomes more rewarding with smaller α. The reverse holds true as well. Therefore, a firm's investment on innovation is highly dependent on the knowledge of competitor's endowment.

Prototype Mimicking and Technology Learning

Based on the analysis of innovation, we can characterize the firm's prototype mimicking and technology learning decision under each openness strategy profile. The prototype mimicking occurs when either one or both firms release the prototype, that is, {P, P}, {P, C}({C, P}) and {O, P}({P, O}). Similarly, the technology learning occurs when one or both firms open the technology, that is, {O, O}, {O, P}({P, O}) and {O, C}({C, O}). Because of the different realizations of two-dimensional uncertainty on initial value and extensibility of technology, we need to consider six scenarios in which technology learning (i.e., through technology openness) can emerge. Considering firm i opens its technology and firm j adopts firm i's technology ($i, j = 1, 2$ and $i \neq j$), we define five types of technology learning under the technology openness (where Type 1 involves two scenarios) in Table 3. We summarize the conditions for both prototype mimicking and technology learning in Proposition 2.

PROPOSITION 2. *Firms mimic the competitor's prototype or adopt the competitor's technology under the following conditions (i, j* = 1, 2 *and* i ≠ *j): (i) when firm i releases its prototype and* $v_{io} = v_H$, $v_{jo} = v_L$, *firm j mimics firm i's proto-*

Table 3. Technology Learning Type

Technology Learning Type	Firm *i*	Firm *j*
Type 1	$v_{i0} = v_{j0}$, $\theta_i = 1$	$v_{j0} = v_{i0}$, $\theta_j = \theta$
Type 2	$v_{i0} = v_H$, $\theta_i = 1$	$v_{j0} = v_L$, $\theta_j = 1$
Type 3	$v_{i0} = v_H$, $\theta_i = \theta$	$v_{j0} = v_L$, $\theta_j = \theta$
Type 4	$v_{i0} = v_H$, $\theta_i = 1$	$v_{j0} = v_L$, $\theta_j = \theta$
Type 5	$v_{i0} = v_H$, $\theta_i = \theta$	$v_{j0} = v_L$, $\theta_j = 1$

Note: Firm *i* opens its technology and firm *j* adopts firm *i*'s technology (*i, j* = 1, 2 and *i* ≠ *j*). In Type 1 technology learning, both firms realize the same initial values (v_H or v_L).

type if $f_p \le f^{PP}$ *under {P, P}, if* $f_p \le f^{OP}$ *under {O, P}({P, O}), or if* $f_p \le f^{PC}$ *under {P, C}({C, P}); (ii) when firm i opens its technology, Type n (n* = 1, 2, 3, 4, 5*) learning occurs if* $f_O \le f_n^{OO}$ *under {O, O}, if* $f_O \le f_n^{OP}$ *under {O, P}({P, O}), or if* $f_O \le f_n^{OC}$ *under {O, C}({C, O}).*

Detailed thresholds are provided in Appendix B. If firm *i* releases its prototype, the prototype mimicking occurs under the condition when two firms realize different initial technology values and the mimicking cost is not too high. Note that the decision to mimic the other firm's prototype is independent of the realized technology extensibility, because the firm makes the mimicking decision before the extensibility realization. Proposition 2(*i*) suggests that the prototype mimicking is more likely to occur under {P, P} than under {P, C}, as $f^{PC} \le f^{PP}$. The rationale of this result is because the firm with low initial value who chooses closedness will invest more heavily under {P, C} than the same firm who chooses prototype release under {P, P}, which in turn reduces the incentive to mimic the competitor's prototype.

When firm *i* decides to share its technology, the conditions under which firm *j* adopts the shared technology vary depending on the strategy profiles, the difference between the initial technology values, the realizations of firms' technology extensibility, and the magnitude of learning cost. Proposition 2(*ii*) provides the conditions for different types of learning to occur in different scenarios. It can be verified that the threshold for Type 4 learning to occur ($v_{i0} = v_H$, $v_{j0} = v_L$, $\theta_i = 1$, $\theta_j = \theta$) is greater than that for Type 1 learning to occur ($v_{i0} = v_{j0}$, $\theta_i = 1$, $\theta_j = \theta$) . This suggests that if firm *i* possesses high technology extensibility, then firm *j* with low extensibility has more incentive to adopt *i*'s technology when firm *i* is also better than *j* in terms of initial value than when two firms have the same initial value. Further, the threshold for Type 4 learning to occur is also greater than that for Type 2 ($v_{i0} = v_H$, $v_{j0} = v_L$, $\theta_i = \theta_j = 1$) learning to occur, and the threshold for Type 3 learning ($v_{i0} = v_H$, $v_{j0} = v_L$, $\theta_i = \theta_j = \theta$) is greater than that for Type 5 learning ($v_{i0} = v_H$, $v_{j0} = v_L$, $\theta_i = \theta$, $\theta_j = 1$). This result is in line with expectation as firm *j* with v_L has more incentive to adopt firm *i*'s technology with v_H when *j*'s extensibility is low than when *j*'s extensibility is high.

One might intuitively expect that technology transfer (i.e., through either technology learning or prototype mimicking) is more likely to occur under technology openness than prototype release. Recall that the ease or difficulty of technology transfer is measured by the thresholds of learning cost and mimicking cost. That is, the higher those thresholds are, the more likely it is that technology transfer can be achieved. By comparing two symmetric profiles {O, O} and {P, P}, our analysis reveals that, counter to the intuition, technology openness does not necessarily incentivize technology transfer more than the prototype release does, as we find that the cost thresholds of mimicking are higher than those of the technology learning in most cases.

Technology Openness Strategy and Subsequent Impacts

After exploring the subsequent stages, this section studies the equilibrium of firms' decisions on technology openness strategy (i.e., technology openness, prototype release and technology closedness). Technology openness represents the commitment that a firm shares her proprietary technology. Consequently, this behavior will reveal the firm's private information of initial value and extensibility of the shared technology. Prototype release denotes the disclosure of an early product to evaluate its design and basic functionalities. As a result, prototype release also releases the firm's private information of the initial value but not the extensibility of technology, because the underlying technology is closed to the competitor. Technology closedness simply means that the firm keeps information about their technology and prototype secret, so the competitor cannot be aware of either initial value or extensibility of her technology.

At a conceptual level, there exist two simultaneous consequences associated with technology openness and prototype release. On the one hand, technology openness or prototype release leads to information leakage to the competitor. Specifically, the firm that chooses to share the prototype or technology will reveal the initial value of the technology (i.e., prototype release) or both the initial value and extensibility of the technology (i.e., technology openness). On the other hand, technology openness or prototype release also yields the possibility of technology learning or prototype mimicking from the competitor. Correspondingly, we term these two effects driven by the openness decisions (1) *information effect* and (2) *access effect*. There are two building blocks in the information effect, which are external and internal information effect. The external information effect denotes the disclosure of the initial technology value, which can be achieved through either prototype release or technology openness. The internal information effect represents the disclosure of technology extensibility and it can be only achieved through technology openness. Technology openness contains both the internal and external information effect while the prototype release only includes the external information effect. The access effect is defined as the possibility of technology transfer through either prototype release or technology openness. Next we compare technology openness with prototype release, then consider the firm's equilibrium technology openness decisions by incorporating technology closedness as well.

Technology Openness Versus Prototype Release

One might reasonably guess that firms always prefer prototype release to technology openness, because prototype release carries the benefits of information effect while not disclosing the complete technology to the competitor. However, our analysis reveals that this conjecture is not always true. We summarize the results that firms have the choice between technology openness and prototype release in Proposition 3. The superscript *OP* represents the scenario {O, P} in which firm 1 chooses technology openness and firm 2 chooses prototype release.

PROPOSITION 3. *The decision between technology openness and prototype release is as follows:*

(i) When technology learning cost $f_O > \overline{f}^{OO}$, *firms prefer technology openness.*

(ii) When $f_O \leq \overline{f}^{OO}$,

(a) if $E\left(\pi_1^{OP}\right) > E\left(\pi_1^{PP}\right)$ *and* $E\left(\pi_2^{OO}\right) > E\left(\pi_2^{OP}\right)$, *firms choose technology openness.*

(b) if $E\left(\pi_1^{OP}\right) \leq E\left(\pi_1^{PP}\right)$ *and* $E\left(\pi_2^{OO}\right) \leq E\left(\pi_2^{OP}\right)$, *firms choose prototype release.*

(c) if neither conditions are satisfied, one firm chooses technology openness and the other chooses prototype release.

Recall that f_O denotes the learning cost under technology openness. Interestingly, we find that firms actually prefer technology openness to prototype release when the technology learning cost is relatively high in Proposition 3(*i*). With high learning cost, if two firms realize different initial values or different extensibility of technology or both, the low firm always insists on its own technology even though the advanced technology is available. This is because the high learning cost prohibits the low firm's adoption of the shared technology. As a result, only the information effect becomes active, which benefits the firm that shares the technology. Further, technology openness carries a stronger information effect than prototype release does as it discloses not only the initial technology value but also its extensibility as compared to the initial value alone in prototype release. Consequently, the equilibrium decision is technology openness in this region (i.e., {O, O}).

When technology learning cost is not high as in Proposition 3(*ii*), our analysis shows that the low firm's decision of adopting the more advanced technology depends on both its own openness strategy (O or P), and the realizations of initial value and extensibility of the shared technology, which leads to the scenario that low firm may or may not adopt the shared technology in this region. Both the information effect and access effect can become active and be the dominant one in this region. Consequently, we obtain the unique symmetric equilibrium {O, O} in (*ii.a*) and {P, P} in (*ii.b*), and asymmetric equilibriums {O, P} and {P, O} in (*ii.c*) as well. The occurrence of the asymmetric pure strategy equilibriums in (*ii.c*) suggests that there also exists a unique, symmetric, mixed-strategy equilibrium, which is provided in Appendix B. The asymmetric equilibriums illustrate that under certain conditions (*ii.c*) asymmetric decisions on technology openness strategy can produce a win-win outcome, increasing both firms' equilibrium payoffs compared with the scenario where they follow the same strategy. Essentially, the choice of a different strategy effectively allows the firm to establish the best response. The asymmetric equilibriums in our model are similar to those in the classic "Battle of the Sexes" game, in which neither equilibrium can be easily distinguished. In practice, firms may be differentiated in terms of their ability to disclose the technology, or release the prototype, which in

Table 4. Technology Openness Equilibriums

Learning Cost/Mimicking Cost		Equilibrium Strategy
(*i*) $f_O > \bar{f}^{OO}$		{O, O}
(*ii*) $f_O \le \bar{f}^{OO}$	a. $f_P > f^{PP}$	{O, O}, if $\begin{cases} E(\pi_1^{OP}) > E(\pi_1^{PP}) \\ E(\pi_2^{OO}) > E(\pi_2^{OP}) \end{cases}$
		{P, P}, if $\begin{cases} E(\pi_1^{OP}) \le E(\pi_1^{PP}) \\ E(\pi_2^{OO}) \le E(\pi_2^{OP}) \end{cases}$
		{O, P} or {P, O} under other conditions
	b. $f^{PC} < f_P \le f^{PP}$	{O, O} under condition C1 {P, C} or {C, P} under condition C2 {O, P} or {P, O} under condition C3 {O, C} or {C, O} under condition C4
	c. $f_P \le f^{PC}$	{O, O}, if $\begin{cases} E(\pi_1^{OC}) > E(\pi_1^{CC}) \\ E(\pi_2^{OO}) > E(\pi_2^{OC}) \end{cases}$
		{C, C}, if $\begin{cases} E(\pi_1^{OC}) \le E(\pi_1^{CC}) \\ E(\pi_2^{OO}) \le E(\pi_2^{OC}) \end{cases}$
		{O, C} or {C, O} under other conditions

Note. The detailed expressions for the thresholds and conditions are provided in Appendix B.

turn, can help resolve the coordination challenge because one of the asymmetric equilibriums would then be considered more focal by the firms. Farrell (1987) and Balasubramanian et al. (2015) have provided excellent discussions about the coordination issue of asymmetric equilibriums.

The Equilibrium Strategy

In the previous subsection, we focused on the comparison between technology openness and prototype release and showed that firms have incentive to share technology in a competitive setting even if prototype release carries similar benefits as technology openness does. Next, we summarize the equilibrium decisions facing the firm when all three technology openness options are available (i.e., technology openness, prototype release and technology closedness). The superscript OC represents the scenario {O, C} in which firm 1 chooses technology openness and firm 2 chooses technology closedness.

PROPOSITION 4. *The equilibriums of technology openness decisions are summarized in Table 4.*

Recall that f_P represents the mimicking cost under prototype release. Proposition 4 shows that when the information effect is active but the access effect is inactive, the firm that opens technology can benefit from unveiling both the initial value and extensibility of technology. Therefore, firms prefer technology openness in region (*i*) of Proposition 4 where the learning cost is high and the access effect is inactivated. In contrast, when the learning cost becomes low, technology learning becomes viable if two firms realize different levels of initial values or extensibility. As a result, the potential loss from the access effect can push the firms to abandon the option of technology openness while choose either prototype release or technology closedness. In specific, when the mimicking cost is relatively high, compared with closedness, prototype release can generate external information effect and benefit both firms, thus the firm chooses between technology openness and prototype release in region (*ii.a*). When the mimicking cost becomes low, the access effect is activated and dominates the benefit from the external information effect under prototype release, leading to the result that the firm chooses between technology openness and closedness in region (*ii.c*). Under moderate mimicking cost, between the two choices, prototype release and technology closedness, one firm would choose prototype release and the other would choose closedness. Eventually, the equilibrium of technology openness strategy relies on the balance between the information effect (from initial value, extensibility or both), the access effect, the technology learning cost, and the prototype mimicking cost, which makes technology openness, prototype release and technology closedness all possible strategy in region (*ii.b*). When multiple asymmetric equilibriums exist, we can also derive the unique, symmetric, mixed-strategy equilibrium; details are provided in Appendix B.

In summary, information effect along with technology openness (i.e., both internal and external information effect) and prototype release (i.e., external information effect) can benefit the firm who shares technology or releases a prototype via suppressing costly innovation competition between the firms. At the same time, technology openness and prototype release also provide an opportunity for the competitor to either acquire the shared technology or mimic the prototype, which in turn hurts the firm who chooses to open the technology or release the prototype. The information effect and access effect create intertwined trade-offs that shape the firm's technology openness decision (i.e., technology openness, prototype release and technology closedness). Technology openness is like a double-edged sword as it carries the strongest information effect to deter costly innovation competition, but it also provides the possibility that the competitor acquires the complete technology. Compared with technology openness, prototype release does not deter competition as effectively as technology openness, but also generates less risk of spilling core technology over to the competitor.

Our analysis reveals that the choice among technology openness, prototype release, and technology closedness is critically moderated by the magnitudes of learning cost and mimicking cost, and the distributions of initial technology value and technology extensibility. When the technology transfer cost (i.e., learning cost or mimicking cost) is relatively high, such a substantial cost can inactivate the access effect under technology openness or prototype release. Meanwhile, the transfer cost thresholds are also closely dependent on the difference between initial technology values, the possible extensibility and firms' openness decisions. We show that the transfer cost thresholds weakly increase in the difference of initial technology values as the potential benefit of acquiring/mimicking the other's technology/prototype increases.

The Impacts of Openness on Innovation and Consumer Surplus

The previous section identifies the conditions under which a firm will share its technology or release a prototype in a competitive setting. An interesting direction is to explore the impacts of openness decisions on subsequent innovation and consumer surplus. As we are mainly interested in the implications of technology openness, we focus on the comparison between technology openness and technology closedness. Following the definition in Xu et al. (2012) and Geng and Lee (2014), we define the consumer surplus as the total monetary gain obtained by consumers. As innovation investment decisions are made after firms realize their endowments, we characterize innovation and consumer surplus as being contingent on different realizations of initial value and extensibility. Interestingly, our analysis reveals that compared with technology closedness, technology openness does not necessarily generate higher innovation levels or greater consumer surplus. We summarize the conditions where a firm's innovation level and consumer surplus both decrease in the following proposition.

PROPOSITION 5. *Compared with technology closedness, (a) when both firms realize high initial value and high extensibility (i.e.,* $v_{i0} = v_{j0} = v_H$ *and* $\theta_i = \theta_j = 1$*), technology openness reduces the innovation of both firms as well as the consumer surplus; (b) when both firms realize high initial value but different extensibility (i.e.,*$v_{i0} = v_{j0} = v_H$ *and* $\theta_i \neq \theta_j$*), technology openness reduces the innovation of both firms and the consumer surplus under the condition of* $v_H - v_L \geq \Delta v_1$*; (c) when both firms realize different initial values but the same high extensibility (i.e.,* $v_{i0} \neq v_{j0}$ *and* $\theta_i = \theta_j = 1$*), technology openness reduces the innovation of both firms and the consumer surplus under the condition of* $v_H - v_L \leq \Delta v_2$.

Δv_1 and Δv_2 are provided Appendix B. Conventional knowledge suggests that technology openness is likely to induce higher innovation activities (i.e., altruism of technology openness) and consequently benefits the consumer. However, our analysis reveals that this conjecture is not necessarily true. Proposition 5 summarizes the conditions when the innovation and consumer surplus will actually drop under technology openness.

Specifically, when both firms realize high endowments in both initial value and extensibility (case *a*), the firms invest less under technology openness than that under technology closedness. The intuition of this result is because under technology openness, firms are aware of each other's technology. As a result, they compete less strenuously by reducing innovation, which consequently hurts the consumer surplus. When both firms have the same high initial value but different extensibility (case *b*), technology openness can also suppress innovation investment and hurt consumer interest. This result holds true when the potential difference between initial values is large. To see the intuition of this result, note that when the potential difference between initial values is large, firms invest very aggressively in anticipation of facing a low initial value firm under technology closedness. However, this intensive innovation investment no longer holds when both firms realize that they actually face a high initial value competitor under the technology openness. When both firms have different initial values but the same high extensibility (case *c*), technology openness has two simultaneous consequences. On the one hand, it incentivizes the firm with high initial value to invest more aggressively because this firm realizes that the competitor has a low initial value. On the other hand, technology openness also discourages innovation investment for the firm with high initial value, since she now realizes that the competitor has the same high extensibility, which suggests that some of their innovation investments will be competed away. As a result, the latter effect dominates the former when the difference between the initial values is small enough.

In summary, we illustrate that technology openness can actually hinder innovation activities and hurt consumer surplus when certain conditions are met. Thus, we argue that technology openness is a well-calculated strategy decision (i.e., shrewd business) that, from a welfare perspective, may create some undesirable outcomes. From a practical perspective, it has been reported that Detroit's Big Three (i.e., General Motors, Ford, and Chrysler) have shown little to no interest in the recently released Tesla patents (Loveday 2014). Recently, Mahindra & Mahindra, one of the largest vehicle manufacturers in India, decided not to use the Tesla patents after two years of very careful review of Tesla's shared intellectual properties (Furtado 2016). Our findings also resonate with the recent leading article in the *Harvard Business Review*, in which Wessel (2018) points out that high-tech firms can use their strength to vanquish potential competitors, and consequently, these leading firms can increase profits without much innovation investment, which hurts consumers. These examples clearly illustrate that a firm's technology openness decision does not incentivize additional innovation activities but serves as a shrewd business decision to drive away market competition, possibly hurting consumers in the end.

Model Extensions

In this section, we extend our base model in three directions. To begin with, we consider the situation in which the firm that shares technology cannot observe the learning behavior of the competitor. Second, we analyze an alternative timing of technology sharing in which the firms make the openness decisions after realizing types. Third, we investigate the scenario where two firms make innovation decisions sequentially. We illustrate that our main results from the base model are robust to these alternative model specifications. In the base model, we explicitly capture the two distinct dimensions of technology openness in terms of information disclosure: initial value and extensibility of technology. Our analysis reveals that information effects along with initial value and extensibility have similar impacts on firms' technology openness decisions. As a result, to focus on the central theme regarding technology openness decision in several modeling alternatives, we make a simplified assumption of the information effect in the extended models. Specifically, we reduce the two dimensions of information disclosure (i.e., initial value and extensibility) to one (i.e., technology capability).

In the extensions, we assume that the consumer's valuation for firm *i*'s product is $v_i = \varepsilon_i + e_i$,[9] where the parameter ε_i represents the capability of firm *i*'s technology ($i = 1, 2$) and e_i denotes the additional value generated through the innovation. There are two possible capabilities for each firm's initial technology *ex ante*; that is, $\varepsilon_i = \varepsilon_H$ with probability β and $\varepsilon_i = \varepsilon_L$ with probability $1 - \beta$, where $\beta \in (0, 1)$. Hereafter, we use high type (low type) to denote the realization of capability ε_H (ε_L). Note that the information disclosure along with technology openness has been reduced to one dimensional information (i.e., capability of the technology). Therefore, the firm only needs to decide whether or not to disclose this information. That is, the firm only needs to choose between technology openness and technology closedness.

Unobservability of Learning

In the base model, we consider the setting when one firm decides to open technology, it can always observe whether the competitor adopts the shared technology or not. However, it's also plausible that the firm who shares the technology may not be able to observe whether the competitor adopts the shared technology or not.[10] Hence, we extend the base model to incorporate this possibility, in which the learning behavior is unobservable. Two firms can choose strategies of openness and closedness at the openness commitment stage, generating

[9]Note that ε_i has a subtle difference compared with the initial value in the base model. In the base model, we assume that the valuation of firm *i*'s product is $v_{i0} + \theta_i e_i$. That is, the innovation (e_i) takes both additive (v_{i0}) and multiplicative form (θ_i) on the initial technology. To make the extended models tractable and retain the key focus on technology openness, we simplify the base model by setting the extensibility to be a constant (i.e., $\theta_i = 1$) and the innovation works on the initial technology through an additive form only. As a result, ε_i completely captures the initial technology in the revised model.

[10]We thank the associate editor for pointing out this interesting research direction.

four strategy profiles, that is, {O, O}, {O, C}, {C, O} and {C, C}. Due to the page limit, we leave the details of the analysis in Appendix C. Next, we present the firm's technology openness equilibrium in the following proposition, where the subscript U represents unobservability of learning.

Proposition 6. *The equilibrium of technology openness or closedness under unobservability of learning is as follows:*

(i) When $f_O > f_{U2}^{OO}$, *both firms prefer technology openness.*

(ii) When $f_{U1}^{OO} < f_O \le f_{U2}^{OO}$: *(a) under the equilibrium selection rule of greater joint profits for two type firms, both firms prefer technology openness; (b) under the equilibrium selection rule of higher profit for the low capability firm, both firms prefer technology closedness if* $f_{U1}^{OO} < f_O \le f_{U2}^{OC}$, *and one firm chooses technology openness and the other chooses technology closedness if* $f_{U2}^{OC} < f_O \le f_{U2}^{OO}$.

(iii) When $f_O \le f_{U1}^{OO}$, *both firms prefer technology closedness.*

Proposition 6 shows that our main results from the base model remain robust when the learning behavior is unobservable. When the technology learning cost is high as in Proposition 6(*i*), the access effect of technology openness is deactivated and both firms can benefit from the information effect. In contrast, when the learning cost is low as in Proposition 6(*iii*), the access effect becomes activated and both firms choose technology closedness to avoid the loss from the access effect. When the learning cost is moderate, different from the observable case where the low type firm always adopts the technology from the high type firm (if available), we find that under the unobservability case, either the learning or no learning can constitute the equilibrium under {O, O} if $f_{U1}^{OO} < f_O \le f_{U2}^{OO}$ and under {O, C} ({C, O}) if $f_{U1}^{OC} < f_O \le f_{U2}^{OC}$, where $f_{U1}^{OO} \le f_{U1}^{OC} \le f_{U2}^{OC} \le f_{U2}^{OO}$.

Facing the multiple equilibriums involving both learning and no learning with associated innovation, we can apply different rules to single out the pure strategy equilibrium. As suggested in the literature (e.g., Bajari et al. 2010, Ellickson and Misra 2011), we can apply the equilibrium selection rule of greater joint profits for two type firms, and based on this rule learning does not occur when $f_{U1}^{OO} < f_O \le f_{U2}^{OO}$ under {O, O} and when $f_{U1}^{OC} < f_O \le f_{U2}^{OC}$ under {O, C}. Therefore, in the region of $f_{U1}^{OO} < f_O \le f_{U2}^{OO}$, no access effect happens under {O, O} and both firms benefit from the information effect by choosing technology openness. If we apply the equilibrium selection rule of higher profit for the low capability firm (e.g., Guo and Jiang 2016), learning occurs and access effect is activated when $f_{U1}^{OO} < f_O \le f_{U2}^{OO}$ under {O, O} and when $f_{U1}^{OC} < f_O \le f_{U2}^{OC}$ under {O, C}, which implies that learning is more likely to happen under {O, O} than {O, C} since $f_{U2}^{OC} \le f_{U2}^{OO}$. As a result, when $f_{U1}^{OO} < f_O \le f_{U2}^{OC}$, {C, C} becomes the unique equilibrium; when $f_{U2}^{OC} < f_O \le f_{U2}^{OO}$, {O, C} and {C, O} become the equilibriums since the access effect is deactivated in this region.

Interestingly, it can be verified that if the learning behavior is observable, the openness strategy is identical to that under the unobservability case when the equilibrium selection rule is based on higher profit for the low capability firm. When the equilibrium selection rule is based on greater joint profits for two type firms, technology openness is more likely to be the decision under unobservability than under observability. The rationale of this result is because when the learning behavior is observable, the high type firm makes the innovation investment after observing the low type firm's learning decision accordingly. However, when the learning behavior is unobservable, the high type firm tends to make excessive innovation investment due to its uncertainty about the competitor's learning action, generating the coexistence of learning and no learning equilibriums, which reduces the competitor's incentive to adopt the shared technology, and in turn increases the incentive for the firm to share its technology. Consequently, based on the above analysis, we conclude that firms are more likely to choose technology openness strategy when the learning behavior is unobservable than when the learning behavior is observable.

Open Procrastination

In the base model, we analyze the firm's decision on technology openness before it fully realizes the capability (type) of the initial technology.[11] A natural and intriguing question here is what the equilibrium will be if firms make openness decisions after they realize their types. To address this, we consider an alternative timing structure in this subsection. Specifically, two firms make their openness decisions after realizing the capability of their own technology, which we define as the procrastinated openness stage. Let $\delta_i(\varepsilon_i)$ denote the decision of firm i with capability ε_i, where $\delta_i(\varepsilon_i) = 1$ if firm i chooses to open and $\delta_i(\varepsilon_i) = 0$ if firm i chooses to close (i = 1, 2). Therefore, firm i's decision under open procrastination can be represented as ($\delta_i(\varepsilon_H)$, $\delta_i(\varepsilon_L)$). Our analysis here focuses on the symmetric rules since firms are *ex ante* sym-

[11] We thank the anonymous reviewer who suggested this line of investigation.

Table 5. Possible Pure Strategies for Delayed (Procrastinated) Decision on Openness

		Low Type Firm $\delta(\varepsilon_L)$	
		Openness	**Closedness**
High Type Firm $\delta(\varepsilon_H)$	**Openness**	{1, 1}	{1, 0}
	Closedness	{0, 1}	{0, 0}

etric, which means that both firms will make the same decision if they share the same capability. That is, $(\delta(\varepsilon_H), \delta(\varepsilon_L)) = (\delta_i(\varepsilon_H), \delta_i(\varepsilon_L)) = (\delta_j(\varepsilon_H), \delta_j(\varepsilon_L))$ $(i, j = 1, 2; i \neq j)$. In fact, since the realizations of their capability types are stochastic, firms could still become asymmetric at the stage of making the procrastinated decision on openness. As a result, there are four pure strategies for the firms to consider before the innovation investment stage shown in Table 5.

In the dynamic game of incomplete information, $(\delta(\varepsilon_H), \delta(\varepsilon_L)) = (1, 0)$ and $(0, 1)$ are separating equilibriums since firms with different capabilities make different decisions, while $(\delta(\varepsilon_H), \delta(\varepsilon_L)) = (1, 1)$ and $(0, 0)$ are pooling equilibriums because firms with different types make the same decision. Note that during the procrastinated openness stage, firms make openness decisions based on the capability realization of technology, forming a signaling game between them. The signal is the decision of openness or closedness, and firms make investment decisions on innovation after observing the signal. The unique feature of this setting is that the two firms are both signal senders and receivers, in which both of them send signals simultaneously and receive after that. Each firm uses Bayes' rule to update posterior belief about the competitor's type according to the competitor's signal. Use $\xi(\varepsilon_H|\delta(\varepsilon_i))$ to denote the belief that firm j assigns type ε_H to firm i after observing the decision signal $\delta(\varepsilon_i)$ of firm i, and probability $1 - \xi(\varepsilon_H|\delta(\varepsilon_i))$ to type ε_L of firm i. The (pure-strategy) perfect Bayesian equilibrium (PBE) of the signaling game is summarized in the following Proposition 7.

Proposition 7. *(i) When $f_O \le f_{U2}^{OC}$, there exists a unique pooling PBE: Close the technology for both types. Specifically, $(\delta^*(\varepsilon_H), \delta^*(\varepsilon_L)) = (0, 0)$ with posterior belief $\xi(\varepsilon_H|0) = \beta$. (ii) When $f_O > f_{U2}^{OO}$, there exists a unique separating PBE: Open the technology when type is high and close the technology when type is low, that is, $(\delta^*(\varepsilon_H), \delta^*(\varepsilon_L)) = (1, 0)$ with the beliefs $\xi(\varepsilon_H|1) = 1$ and $\xi(\varepsilon_H|0) = 0$. The subsequent innovation levels of each PBE are provided in Appendix C.*

Proposition 7(i) shows that when $f_O \le f_{U2}^{OC}$, firms of both types choose pooling on the closedness strategy. The intuition of this finding is that when $f_O \le f_{U2}^{OC}$, the access effect is activated. As a result, no matter which pooling strategy the competitor chooses (i.e., openness or closedness), the high type firm will suffer from disclosing the technology, which leads closedness to be a strictly dominant strategy. For the low type firm, when she can learn the rival's advanced technology (if the rival chooses pooling on openness under $f_O \le f_{U2}^{OC}$), both options are equivalent. However, when the rival chooses pooling on closedness, the information effect alone hurts the low type firm, and thus the weakly dominant strategy is to close. In summary, both types of firms prefer to conceal their technology when the learning cost is relatively low, but the rationales are quite different: The high type wants to avoid copycats whereas the low type wants to avoid disclosing its technology disadvantage.

Proposition 7(ii) shows that when $f_O > f_{U2}^{OO}$, the unique separating equilibrium is that high type chooses to open while low type chooses to close. Note that under the separating strategy, the firm's decision of either openness or closedness will inevitably reveal their type. Therefore, the information effect always exists in both separating strategies (i.e., (1,0) and (0,1)). Suppose that firm i chooses (1, 0) and holds consistent belief on firm j's strategy, and firm j recognizes it and holds the same belief. For firm j of low type, she is indifferent toward the two separating strategies; for firm j of high type, she obtains the incentive of deviating from (1, 0) to (0, 1) due to the activation of access effect when $f_O \le f_{U2}^{OO}$, while no deviation incentive exists when $f_O > f_{U2}^{OO}$. Therefore, a separating strategy (1, 0) with corresponding beliefs forms an equilibrium given the condition $f_O > f_{U2}^{OO}$. When firm i chooses (0, 1) and has a consistent belief regarding firm j, firm j of low type always has the incentive to deviate from (0, 1) to (1, 0). Firm j of high type prefers (0, 1) to (1, 0) when $f_O \le f_{U2}^{OO}$ while she is indifferent to the two separating strategies when $f_O > f_{U2}^{OO}$, suggesting that (0, 1) is not a separating equilibrium. Note that at the current signaling game of a procrastinated openness decision, since different types of firms make different decisions when $f_O > f_{U2}^{OO}$, that is, (1, 0), the disclosure of private information is realized, which yields similar results as *ex ante* open commitment.

Sequential Innovation

In our base model, we consider that two firms make their innovation investment decisions simultaneously. One may argue that the innovation competition can also occur sequentially. That is, the incumbent firm makes its innovation decision first and then the entrant decides its innovation level after observing the value of the incumbent's product.[12] To accommodate this possibility, we extend the base model to a Stackelberg game where firms make their innovation decisions sequentially. The timing of this extension is similar to the base model, except that in this setting firms make the innovation decisions one after the other. In this subsection, we refer to the incumbent as firm 1 and the entrant as firm 2, and use the subscript S to represent the sequential innovation. We characterize the equilibrium result of the openness strategy in the next proposition and the sequential innovation decisions are provided in Appendix C.

Proposition 8. *Under sequential innovation, we have:*

(i) When $f_O > f_{S1}^{OO}$, the entrant prefers technology openness, and the incumbent is indifferent between technology openness and closedness.
(ii) When $f_{S2}^{OC} < f_O \leq f_{S1}^{OO}$, the entrant prefers technology closedness, and the incumbent is indifferent between technology openness and closedness.
(iii) When $f_O \leq f_{S2}^{OC}$, both incumbent and entrant prefer technology closedness.

Similar to the Proposition 4 in the base model, we find that the learning cost critically moderates the firm's technology openness decision. In specific, the above proposition suggests that when the learning cost is relatively high (i.e., $f_O > f_{S1}^{OO}$), due to the benefit of the information effect and deactivated access effect, the entrant chooses to share the technology, while the incumbent is indifferent between technology openness and closedness strategy. Note that the entrant (firm 2) can always observe the value of the incumbent's (firm 1) product before making her own innovation decision. In specific, if the incumbent chooses the technology openness, the entrant can observe both the capability (i.e., ε_1) and the innovation (e_1) of the incumbent. If the incumbent chooses the technology closedness, the entrant can still observe the overall value of the incumbent's product (i.e., $v_1 = \varepsilon_1 + e_1$). That is, sequential innovation ensures that the entrant can always be aware of the incumbent's information. As a result, the incumbent is indifferent between the technology openness and closedness strategy. When the learning cost is moderate (i.e., $f_{S2}^{OC} < f_O \leq f_{S1}^{OO}$), the incumbent will adopt the entrant's technology if the entrant chooses technology openness. As a result, the entrant chooses technology closedness. Further, we can show that in this region the entrant will not exert the learning cost to adopt the incumbent's technology even if the incumbent chooses to open technology. Therefore, the incumbent is again indifferent between technology openness and closedness. When the learning cost is low, technology closedness is preferred by both firms to avoid the damage from the access effect.

In summary, the above proposition not only shows that the main tradeoff from base model remains qualitatively the same under sequential innovation decisions, but also contributes to a new insight. We find that when the learning cost is from moderate to high, the incumbent is indifferent between technology openness and closedness. From the incumbent's perspective, the value of incumbent's product is always revealed to the entrant in either technology openness or closedness. Further, from the entrant's perspective, the entrant expects that the incumbent can gain a higher market share by investing heavily in innovation, which reduces the entrant's incentive to adopt the incumbent's shared technology if the incumbent chooses technology openness. Both reasons contribute to this new finding.

[12]We thank the senior editor who encouraged us to explore this interesting direction.

Managerial Implications and Future Research

Managerial Implications

Motivated by the proliferation of technology openness, the goal of this research is to explain why firms are willing to share their proprietary technologies with competitors. Existing literature has argued that technology openness increases the adoption of shared technology through network effects on the demand side. Essentially, it benefits firms when the enlarged market from network effects outweighs the cannibalized market from technology access by the competitor. Our research complements the existing literature by exploring an alternative benefit of technology openness from the supply side. We show that, even in the absence of network effects, technology openness can benefit the firms that choose to share their technology by reducing costly innovation competition.

Specifically, we construct a model of three different options of technology openness strategies: technology openness, prototype release, and technology closedness. If the firm chooses technology openness, then the competing firm will be aware of both the initial value of her technology as well as the extensibility of that technology. If the firm chooses prototype release, then the competing firm will be aware of the initial value of her technology, but not the exact level of extensibility of that technology. Our analysis reveals that firm's technology openness decision is critically dependent on the trade-off between the information effect and the access effect. The information effect along with technology openness (i.e., both internal and external information effect) and prototype release (i.e., external information effect) can benefit the firm that shares the technology/prototype by suppressing costly innovation competition between the firms. At the same time, technology openness and prototype release also provide an opportunity for the competitor to either acquire the shared technology or mimic the prototype (i.e., access effect), which hurts the firm that chooses to share the technology or prototype. Thus, the trade-off between the information effect and the access effect shapes the firm's technology openness decision. We further illustrate that our main findings are robust by considering the unobservability of learning, alternative timing of the openness decision, and sequential innovation.

Our study provides several interesting managerial insights to firms as well as policy makers. To begin with, we find that, while a firm's openness strategy may be interpreted as an altruism, it can also financially benefit the firm itself. We characterize the conditions of when and how technology openness can benefit firms that choose to share their proprietary IP. Echoing Teece (1986), when technology learning is resource intensive, learning costs can provide a shield for the firm that chooses technology openness; when learning costs are relatively low, technology openness may give competitors the opportunity for a free ride, leading to unfavorable consequences for the firm choosing openness. Further, we would also suggest a cautionary note to policy makers about innovation activities and consumer surplus under technology openness. Conventional knowledge suggests that technology openness is likely to induce higher innovation and consequently benefits the consumer. However, our analysis reveals that a firm's technology openness does not necessarily incentivize additional innovation activities or benefit consumers. Specifically, we identify the conditions when technology openness can actually hinder innovation activities and diminish consumer surplus. This finding resonates with that of Wessel (2018) who cautions policy makers that high-tech firms can use their strength to deter potential competitors, and consequently, these leading firms can increase profit without significant innovation investment, which ultimately harms consumers. The above findings provide interesting and testable hypotheses for the future researchers in this area.

Limitations and Future Research Opportunities

We briefly point out a few limitations and outline some directions for future research. To begin with, many software products are coupled with hardware products (Hao and Fan 2014). The firm needs to take complementary product markets into consideration when they make the decision regarding technology openness. We exclude complementary markets in this paper in order to rule out the impact of network effects. Future research can explore how the complementary market shapes the firms' decision on openness and innovation. Second, this paper mainly focuses on the innovation actions of IT products and thus ignores production cost. In fact, our theory can be easily extended to other industries that emphasize both innovation and production (e.g., bio-pharmaceuticals and automobiles). In such cases, the production cost of the final product is closely related to the innovation degree (quality) of the product, and the cost could even be nonlinear. Therefore, how the interplay between innovation and production affects technology openness strategy for competing firms is a meaningful future topic at the intersection of R&D and production. Third, this paper mainly focuses on the vertically integrated firm (Parker and Van Alstyne 2018) in which the innovation is conducted by the firm that developed the original technology. Future research can extend the model to allow third-party developers to make innovations on the core technology. Finally, we only study the impact of unobservable learning between technology openness and technology closedness. Future studies can investigate the impact of unobservability in prototype mimicking as well. Notwithstanding these limitations, this study contributes to the emerging literature on technology openness by revealing a novel explanation for why firms are willing to disclose their technologies. These results complement and extend the previous literature which concentrates primarily on network effects.

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Appendix A

Comparison between Related Works in Information Sharing and Technology Openness with Current Study[13]

Published Studies	Sharing Structure	Shared Information	Prototype Release	Technology Openness	Impact on Innovation	Main Conclusions
Vives (1984)	Horizontal	Demand				Information Sharing happens when products are substitutes in Bertrand competition or complements in Cournot competition.
Gal-Or (1985)	Horizontal	Demand				No Information sharing happens in oligopoly under a Cournot competition with substitutes products.
Li (1985)	Horizontal	Demand/ Cost				Cournot oligopolists share cost information and do not share demand information.
Gal-Or (1986)	Horizontal	Demand/ Cost				Demand information sharing happens under Bertrand competition, and cost information sharing happens under Cournot competition.
Li (2002)	Vertical	Demand/ Cost				Under Cournot competition, downstream does not voluntarily share demand information with upstream manufacturer, but shares cost information with the manufacturer voluntarily under certain conditions.
Zhang (2002)	Vertical	Demand				Retailers do not share demand information with the manufacturer on a voluntary basis whenever Cournot or Bertrand competition with either substitutes or complements.
Zhu (2004)	Horizontal	Cost				Low-cost firms of substitutes products share their cost information both in Cournot and Bertrand competition, high-cost firms of complements share their cost information when competing in Bertrand.
Ha and Tong (2008)	Vertical	Demand				When manufacturers offer a contract menu, retailers (privately) share information with manufacturers (through a payment) when the cost (system cost) of information sharing is low. When manufacturers offer a linear price contract, retailers do not share information.
Li and Zhang (2008)	Vertical	Demand				Under privately vertical sharing (confidentiality), all parties will voluntarily engage in information sharing if the competition between retailers is intense and the demand information is less accurate.
Zhou and Zhu (2010)	Horizontal	Cost				Downstream firms prefer cost information sharing under Cournot competition, and prefer not to share under Bertrand competition.
Ha et. al (2011)	Vertical	Demand				Retailers share information to their own suppliers when production diseconomy is large through a payment.
Jiang and Hao (2014)	Horizontal	Demand				Firms under cooperation have the incentive to share information that are not perfectly correlated under Bertrand competition.
Li and Zhang (2015)	Vertical	Demand				The retailer voluntarily shares information with its manufacturer if the demand uncertainty is intermediate under monopoly market.
Shamir and Shin (2016)	Vertical	Demand				Information sharing is credible when the incumbent publicly announces the demand forecast.

[13]The published studies are listed in chronological order.

Published Studies	Sharing Structure	Shared Information	Prototype Release	Technology Openness	Impact on Innovation	Main Conclusions
Shang et.al (2016)	Vertical	Demand				A common retailer shares information to the competing suppliers voluntarily when production economy is large.
Jiang and Hao (2016)	Horizontal	Demand				The competition between retailers promotes information sharing between them, while the competition between suppliers precludes vertical information acquisition.
Niculescu et. al (2018)	Horizontal	Technology		✓		When the network effect and absorptive capacity are intermediate, the incumbent opens the technology.
Kwark et. al (2018)	Horizontal	Demand				When firms are uncertain about consumer taste (location, i.e., horizontal differentiation) and correlation-increasing effect between two competing firms is moderate, UGC (information sharing) benefits both firms.
Ha et.al (2017)	Vertical	Demand	✓			Retailers voluntarily share information with their own suppliers when cost reduction is sufficiently efficient.
Qiu et al. 2017	Horizontal	Demand (Asset Value)				Information sharing among participants may help to correct the inefficiency that is generated by the increased precision of public information and improve the prediction market performance.
Current Study	Horizontal	Technology	✓	✓	✓	First, our study provides a novel explanation for firm's technology openness decision from the supply side, while the existing studies mainly focus on the demand side. Second, our study reveals that technology openness does not always lead to the increase of the innovation, which is new to the literature.