PATENT ABANDONMENT AND SUBSEQUENT CUMULATIVE INVENTIONS

BY

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DISSERTATION

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ABSTRACT

This dissertation explores how the focal firm's patent abandonment strategy can facilitate cumulative inventions by external inventors, as well as subsequent cumulative inventions by the focal firm to enable value creation and value capture. To keep a patent in force in the United States, a firm must pay maintenance fees at three subsequent time-periods after the issuance of the patent. The focal firm's patent abandonment reduces transaction costs of external inventors conducting cumulative inventions that build on the focal firm's abandoned patent, which creates a larger and broader knowledge spillover pool. Further, the firm's patent abandonment can be a positive-sum game, in which the focal firm can also benefit by identifying distant knowledge as well as potential new inventors' inventions. This patent abandonment allows the focal firm to learn from the knowledge spillover pool created through its patent abandonment.

Following Chapter 1, which provides the introduction, Chapter 2 examines how the focal firm's patent abandonment influences external inventors conducting cumulative inventions, which build on the focal firm's abandoned patent. I submit that the focal firm's patent abandon-ment opens up invention to the "wisdom of crowds," and reduces external inventors' licensing costs and litigation threats from the focal firm holding the initial patent. Thus, the focal firm's abandoned patent provides external inventors greater opportunities to conduct more research that builds on the focal firm's abandoned patent. Further, a focal firm's patent abandonment could transform its own limited internal and external search into broader external inventors' collective search. Thus, inventions by external inventors in the knowledge spillover pool created through the focal firm's patent abandonment can become both larger and greater breadth. Consistent with this theory development, I corroborate empirically that the focal firm's patent abandonment can increase the amount and breadth of external forward citations of the abandoned patent.

Chapter 3 and Chapter 4 focus on how the focal firm can create and capture value through its patent abandonment. Chapter 3 examines under what conditions the focal firm can learn more from the knowledge spillover pool created through its patent abandonment, which is a necessary condition for the focal firm to create and capture positive economic value from its patent abandonment. I submit that the knowledge spillover pool created by external inventors due to the focal firm's patent abandonment can facilitate the focal firm's subsequent learning and consequently increase its subsequent inventions. Such learning from the knowledge spillover pool by the focal firm is greater when this pool contains higher quality external *inventions* and larger number of external *inventors*. This chapter further explores how moderating factors, such as the focal firm's: (i) explorative search path in its invention creation stage; (ii) internal use of the abandoned patent in its invention development stage; (iii) experience in leveraging external knowledge, and (iv) self-ownership of complementary patents, influence the efficiency and effectiveness of its learning from a more valuable knowledge spillover pool.

Chapter 4 explores how the focal firm can use patent abandonments to overcome its own limited search in subsequent exploration and exploitation of its patent. In particular, I examine which inventions within the knowledge spillover pool developed by external inventors are more likely to be integrated by the focal firm in its subsequent inventions. Through its patent abandonment, the focal firm could then rely on collective search to identify inventions containing knowledge that is more distant and developed by potentially new external inventors, which lowers the cost of the focal firm compared to renewing its patent and conducting its own internal search. Due to the focal firm's path dependent search behavior and its limited absorptive capacity, the focal firm's reliance on external inventors' collective search would likely be more efficient and effective in its familiar domain. The empirical results show that the focal firm is more likely to

integrate external inventors' inventions into its subsequent inventions if the invention is: (i) combined with knowledge that is distant from the focal firm's existing knowledge base; and (ii) created by new external inventors. Furthermore, the focal firm would be more likely to integrate inventions containing knowledge that is more distant and created by new inventors, if the inventions are in the areas where the focal firm has greater technological strength.

The fifth and final chapter offers conclusions, provides research limitations, and suggest future research directions. To address some of these limitations, suggestions for future research that builds on this dissertation are also provided.

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CHAPTER 1: INTRODUCTION

Inventions are becoming cumulative, and typically involve collaboration among multiple inventors to conduct research that builds on the initial invention to bring it to successful commercialization (Alexy, George, & Salter, 2013; Nelson & Winter, 1982). Usually, an invention creates sufficient economic value neither for society nor for the initial inventor without subsequent developments or improvements on this initial invention (Kline & Rosenberg, 1986). Therefore, facilitating cumulative inventions is important for both policymakers and the focal firm's decision makers, especially when the initial invention has little economic value as a stand-alone invention, but can be a foundation for valuable subsequent innovation (Scotchmer, 1991). Policymakers need to consider the incentives provided to the original inventor, as well as to potential (independent or collaborative) follow-on inventors to develop further the initial invention (Sampat & Williams, 2015). Furthermore, the focal firm's decision makers' consideration should not be limited to the development of a single invention, but whether such an invention could create positive/or negative spillovers to the focal firm's subsequent inventions (Kang, Mahoney, & Tang, 2009).

This dissertation considers the focal firm's patent abandonment move from both public policy and strategic management perspectives. In particular, the main research question of the dissertation explores how the focal firm's patent abandonment could influence subsequent cumulative inventions conducted by external inventors, as well as subsequent cumulative inventions conducted by the focal firm. A patent holder must pay three post-issuance maintenance fees to the U.S. Patent and Trademark Office (USPTO) to keep the patent in force. Maintenance fees can be paid without surcharge at 3 to 3.5 years,

7 to 7.5 years, and 11 to 11.5 years after issuance. There are also three half-year "grace periods," during which the patent holder can pay regular maintenance fees and a surcharge due to late payments. The patent is abandoned if the focal firm does not pay any of the maintenance fees and required surcharges by the end of the 4th, 8th, or 12th years after issuance.[1] Once the patent is abandoned, it becomes available in the public domain and free for external inventors to use.[2] Figure 1.1 presents the timeline of the focal firm's patent renewal and abandonment.

The costs of maintaining a single patent is low, relative to large amounts of R&D expenditures in the initial discovery stage (Khanna, Guler, & Nerkar, 2016). However, the data show that, from a population of about 1.2 million patents issued by the USPTO, which were applied by firms between 1981 to 2010 (inclusive), firms abandon about 40% of these patents before their statutory expiration date (of 20 years after the priority -- i.e., effective filing -- date), based on firms' decisions to decline paying maintenance fees. Though firms typically abandon a large number of their patents before their full statutory life, research on the consequences of such patent abandonment is limited. This dissertation seeks to fill this research gap and explores invention after the focal firm's patent abandonment.

[1] The focal firm can still reinstate a patent after its abandonment by paying an additional surcharge, along with evidence to show the initial abandonment was either unavoidable or unintentional. The option to reinstate a patent for unintentional expiration is only available within two years of the expiration date. To reinstate a patent that has expired for more than two years, the focal firm needs to show evidence of an unavoidable expiration, but this criterion is highly unlikely to be met.

[2]Though the patent holder can reinstate the patent that had been abandoned, a reinstated patent does not have the similar strength of the original patent. The follow-on inventors are permitted to acquire the intervening rights to continue using the reinstated patent if, in good faith, it invested money and went into production. Moreover, a patent that lapsed and was later reinstated by the focal firm opens the door to certain attacks that would not be available if the patent had never been abandoned. For example, an alleged infringer could provide documentation showing that the patent reinstated by the focal firm is invalid because it was intentionally abandoned.

The existing literature investigating the focal firm's patent renewal and abandonment decisions typically begins with a fundamental principle of neoclassical economics. The focal firm will choose to renew the patent when the economic value of maintaining its patent exceeds its cost of renewal. Combining this logic with modern financial theory, Pakes (1986) submits that a patent can be viewed as a real option, which gives the patent holder the right (but not the obligation) to pay the renewal fee and maintain the patent in the future should the focal firm desire to do so. As a result, a profit-maximizing firm will only choose to pay the maintenance fee to renew its patent if the sum of its current returns plus the value of this real option exceeds the maintenance fee that is required to pay to the patent office. Based on this economic logic, the research literature illustrates that firms tend to abandon their patents if they perceived them to be of low quality (Liu, Authurs, Cullen, & Alexander, 2008; Lowe & Veloso, 2015; Serrano, 2010). Low quality patents in the focal firm's patent portfolios would typically require the focal firm to spend substantial resources to maintain and could delay negotiations of licensing agreements of other patents.[3] Further, even though the costs of maintaining a single patent might not be high, they are not negligible in aggregate when the focal firm needs to maintain large patent portfolios. Though small firms might not have large patent portfolios to manage, they typically face the financial constraints in maintaining its patents (Moore, 2005). As a result, both large firms and small firms often must abandon some of their patents from their patent portfolios (Lowe & Veloso, 2015; Nerkar & MacMillan, 2003).

[3] See http://www.iam-media.com/Intelligence/IAM-Yearbook/2016/Monetisation-and-strategy/Patent-portfolio-pruning-or-tuning-to-increase-IP-investment-returns

Following on the above logic, one rationale for why the focal firm abandons its patent is because it recognizes its failures in the initial experiment of the technologies (Khanna, Guler, & Nerkar, 2016) and decides to discontinue subsequent development of this technology. The extant literature shows that the focal firm's abandoning its poor patents can increase the value of the focal firm's overall patent portfolios (Lowe & Veloso, 2015). Thus, the literature either applies patent renewal data to estimate the value distribution of the patents (Pakes, 1986), or as a proxy of the private value of the patent (Liu, 2014). Factors posited to reflect the value of the patent, such as characteristics of: the industry (Schankerman, 1998); corporate strategy (Lowe & Veloso, 2015); inventors (Liu, 2014); and technologies embedded in the patent (Thomas, 1999), will influence the focal firm's decision to renew or abandon the patent (Nerkar & Macmillan, 2003). Table 1.1 provides a literature review of the determinants of patent renewal and abandonment.

Overall, the existing literature posits that the focal firm typically chooses "poor" patents to abandon. Further, these abandoned patents are not anticipated to create any economic value to the focal firm. Conventional wisdom suggests that when the focal firm's abandoned patent is later revealed by others to have high technological and market value, this move provides evidence that the focal firm made an error in judgment. The focal firm might lose millions of dollars in patent monetization because of such an error in judgment. Moreover, it might lose more economic value when more inventors that are external innovate by freely using the abandoned patent to create patentable improve-ments, which might block the focal firm from a part of the market that the focal firm originally attempted to capture, and consequently impede the focal firm's subsequent inventions. This dissertation intends to debunk this "conventional wisdom."

Instead of viewing the focal firm's abandoning of a patent, which is later revealed to have high technological and market value, as necessarily leading to a poor outcome for the focal firm, my dissertation offers an alternative explanation of why the focal firm might achieve positive economic value capture through abandoning its patent. Though the focal firm's abandoned patent might not create sufficient economic value for the focal firm at the time of abandonment, the future development of the technology of the abandoned patent is unpredictable because of complexity and uncertainty of successful invention (Landau & Rosenberg, 1986; Rosenberg, 1990). Further, the patent renewal literature does not consider the focal firm's limited explorative and exploitative search concerning its own invention and the potential negative effect of its own patent on external inventions' search behavior (which could potentially help the focal firm) (Harhoff, Scherer, & Vopel, 2003). The "anti-commons" theory[4] suggests that an *over*-protection of the focal firm's initial patent can lead to an *under*-use of knowledge and technology embedded in this initial patent, which thus constrains potential external inventors to develop subsequent cumulative inventions due to the high transaction costs of acquiring the initial patent (Heller & Eisenberg, 1998). Therefore, the focal firm's patent abandonment would encourage external inventors to develop more and broader subsequent cumulative inventions, which are built on this abandoned patent. When knowledge gained and then protected through patents is cumulative, it is possible that technology in the initial patent

[4] As Ostrom (1990) makes clear, the "commons problem," the "tragedy of the commons," the "prisoner's dilemma problem," and the "collective action problem" are closely related. At the heart of each of these problems is the free-rider problem. Because of *under*-defined property rights there can be an *over*-use of resources (e.g., forests and rivers). An "anti-commons problem" is one in which there is an *over*-definition of (overlapping) property rights in which there can be an *under*-use of resources/innovations (e.g., due to "patent thickets") (see, e.g., Galasso and Schankerman, 2015; Murray and Stern, 2007; Ziedonis, 2004).

becomes more valuable after further development by these external inventors (Bessen & Maskin, 2009; Kline & Rosenberg, 1986). Moreover, invention is not necessarily a zero-sum game, but rather can be a positive-sum game, in which the focal firm can also gain positive value capture through learning from these external inventors' subsequent development of its initial abandoned patent. Belenzon (2012) empirically corroborates that a potential negative impact of knowledge spillovers can be mitigated if the inventing firm can re-absorb knowledge in one of its later inventions. Thus, the focal firm might also achieve positive economic value capture if it can generate more inventions in the future through learning from these external inventors' subsequent development of the technology in its abandoned patent. Thus, the value of patent abandonment for society and for the focal firm might be underestimated in the existing patent renewal literature.

This dissertation examines inventions after the focal firm's patent abandonment, which can be described as two stages of invention. Figure 1.2 provides invention moves after the focal firm's patent abandonment. In the first stage, the focal firm's patent abandonment can generate a knowledge spillover pool, which is the collection of patents developed by external inventors through recombining their own complementary knowledge and the knowledge in the focal firm's abandoned patent. I submit that when the focal firm abandons its patent, potential external inventors with relevant knowledge would create a more valuable knowledge spillover pool by developing more and broader cumulative inventions that build on the focal firm's abandoned patent than the counterfactual of when the focal firm renews its patent. In the second stage, due to the focal firm's superior absorptive capacity, capabilities in leveraging external knowledge and holding complementary patents, the focal firm can effectively and efficiently learn from

this valuable knowledge spillover pool. Such learning is enabled by the focal firm's patent abandonment in the first stage, which in the second stage generates inventions based on knowledge within this spillover pool.

Figure 1.3 provides an illustrative example of the focal firm's patent abandonment and subsequent learning from the knowledge spillover pool. National Semiconductor Corp. (NSC) applied for a decoder patent (4584695) in 1983, which was granted in 1986. NSC decided to abandon this decoder patent in 1990 since NSC considered this decoder patent (4584695) was of no potential use at that point. After NSC abandoned the decoder patent (4584695), another company LevelOne Communications (LevelOne) applied a device patent (5068628) building on NSC's abandoned decoder patent in 1990. Subsequently, NSC developed several patents (e.g. 5132633) building on LevelOne's device patent (5068628), which builds on NSC's original abandoned decoder patent (4584695). If NSC never abandoned the decoder patent (4584695) in the first place, LevelOne might not use this decoder patent (4584695) to create the device patent (5068628). Therefore, NSC might not develop efficiently and effectively these new series of patents (e.g., 5132633). To conclude, NSC can achieve positive value creation and capture through its patent abandonment if these newly developed patents (e.g. 5132633) building on LevelOne's device patent (5068628) collectively create more economic value to NSC than the original abandoned patent (4584695).

The dissertation addresses the following research questions:

Chapter 2: *How does the focal firm's patent abandonment influence external inventors to conduct cumulative inventions derived from this abandoned patent*?

Chapter 3: Under *what conditions can the focal firm develop more cumulative inventions that build on external inventors' inventions in the knowledge spillover pool of the focal firm's patent abandonment?*

Chapter 4: *Which external inventors' inventions in the knowledge spillover pool, which builds on the focal firm's abandoned patent, are more likely to be integrated by the focal firm in its subsequent inventions?*

Chapter 2 focuses on the first stage following the focal firm's patent abandonment and explores how the focal firm's patent abandonment decision could influence external inventors' development of cumulative inventions derived from this abandoned patent. This chapter seeks to provide evidence on whether the focal firm's patent abandonment can create a more valuable knowledge spillover pool than the counterfactual of the focal firm's patent renewal. According to anti-commons theory, the expansion of the initial patent might block external inventors from producing subsequent inventions due to the high transaction costs to acquire the initial patent (Heller & Eisenberg, 1998). Due to the focal firm's bounded rationality (Simon, 1947; Williamson, 1975), and limited resources and capabilities (Penrose, 1959), it has limited search in both exploitation and exploration of its patent (Cyert & March, 1963; March, 1991). Therefore, the focal firm is incapable of, or faces high costs in searching and acquiring a more comprehensive set of knowledge required for subsequent development of its original patent. However, if the focal firm abandons its patent, it can open inventions to broader external inventors to collectively search for new knowledge in subsequent development of the focal firm's abandoned patent that could go beyond what the focal firm can do on its own. Therefore, the abandonment of the initial patent will lead to an increase in both the amount and the breadth of subsequent inventions derived from this patent, which can be reflected in the number and distribution of external forward citations to the abandoned patent (Galasso & Schankerman, 2015; Hoetker & Agarwal, 2007; Murray, Aghion, Dewatripont, Kolev, & Stern, 2010; Sampat & Williams, 2015). While some empirical research corroborates an "anti-commons" effect

by showing that a patent significantly reduces subsequent cumulative inventions (Huang & Murray, 2009; Murray and Stern, 2007; Williams, 2003), other research studies find little empirical evidence of an "anti-commons" effect (Hall & Helmers, 2013; Sampat & Williams, 2015). This chapter provides another examination of the "anti-commons" effect by comparing the number of external forward citations of the abandoned patents relative to that of the renewed patents through a difference-in-differences estimation.

Chapter 3 and Chapter 4 focus on the second stage of invention. Chapter 3 first explores the conditions that enable the focal firm to develop more subsequent cumulative inventions by learning from the knowledge spillover pool created though its patent abandonment. The dissertation maintains that the focal firm can achieve positive economic value capture through abandoning its patents if the focal firm's patent abandon-ment can create a more valuable knowledge spillover pool than would exist if the focal firm's patent were renewed, and the focal firm can successfully learn from this spillover pool in its subsequent inventions. Thus, the focal firm's capability in learning from the knowledge spillover created by its own invention could be critical to determine whether it can achieve positive value capture from its patent abandonment (Belenzon, 2012).

I identify four conditions in which the focal firm can learn more effectively and efficiently from the knowledge spillover pool of its patent abandonment. First, the knowledge spillover pool needs to be valuable enough to provide sufficient knowledge for the focal firm to learn from this pool. To make the knowledge spillover pool more valuable, the spillover pool should contain higher quality inventions. Second, to re-absorb knowledge from a valuable knowledge spillover pool more efficiently, the focal firm needs to have greater absorptive capacity, which can be reflected in its prior knowledge

accumulation in the invention creation stage and the subsequent development stage. Third, the focal firm's prior reliance on external knowledge in its inventions contributes to its superior resource and capabilities in leveraging external knowledge, which enable the focal firm to learn more efficiently and effectively from the more valuable knowledge spillover pool. Finally, the focal firm's ownership of more complementary patents can enhance its value appropriation from the valuable knowledge spillover pool.

Chapter 4 examines how the focal firm could use its patent abandonment to overcome its limited internal and external search through relying on external inventors' collective search. In particular, this chapter examines which inventions within the knowledge spillover pool created through the focal firm's patent abandonment are more likely to be integrated by the focal firm in its subsequent inventions. The chapter proposes that the focal firm can use its patent abandonment strategy to motivate external inventors' collective search, which could complement its existing search strategy in identifying inventions containing distant knowledge and created by new and hidden inventors. Further, the focal firm's reliance on external inventors' collective search might tend to be limited in its familiar area due to its bounded rationality and path dependence of its search behavior. The empirical results show that the focal firm is more likely to integrate the inventions within the knowledge spillover pool, which are recombined with knowledge to be distant from its existing knowledge base and developed by new external inventors, in its subsequent inventions. Further, this chapter shows that the focal firm is more likely to integrate inventions with distant knowledge and created by new inventors, if such inventions are in areas where the focal firm has greater technological strength. This chapter suggests that the focal firm's patent abandonment is not just a decision about whether to

continue or terminate a line of research, but can also reveal a transformation of search strategy. The focal firm could rely on external inventors to search for hidden knowledge in a more cost effective way.

To summarize, Table 1.2 displays the research questions, and the main dependent and independent variables in the following chapters. Figure 1.4 presents the structure of the full dissertation.

Tables and Figures

Table 1.1: Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Factors	Influence
Patent System	
Maintenance Cost	• Schankerman and Pakes (1985): If the maintenance cost increases, the optimal number of years of maintaining the patent will be shortened. • Baudry and Dumont (2006): The increase of the renewal fee will, on the one hand, decrease the patent option value of those "patent actually applied for," but on the other hand, increase the patent value through a screening process. The empirical results show that the latter positive impact on the patent value dominates. • Thomas (1999): After patent maintenance fees were doubled for patents applied for after August 1982, a larger proportion of patents is maintained at each renewal point, despite the increase in maintenance fees. • Lanjouw, Pakes, and Putnam (1998): The benefit to patentees of a decrease in renewal fee is twofold: they pay less for each year of protection, and, because it is less costly, they also tend to take advantage of more years of protection.
Application fee	• Baudry and Dumont (2006): Higher initial application fees can weed out patents with low quality.
Grant rate	• Schankerman (1998): The decline in grant rates reflects more stringent screening that weed out low-valued patents. Higher rates for a nationality, within a given technology field is associated with a higher mean value (provided patent screening does not depend on which country applies for the patent).
First-to-invent to first-to-file	• Moore (2005): If the rush to patent is substantial in the present first-to-invent system, it would likely be exacerbated if it changes to a first-to-file system.

Table 1.1(cont.): Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Institutional or Economic factors	
Appropriability environment	• Cornelli and Schankerman (1996, 1999): From the government perspective, the higher the effectiveness of the appropriability environment should be negatively associated with the optimal patent length. From the firm perspective, the greater the appropriability, the longer the time that the firm will keep the patent. • Schankerman (1998): Institutional or economic factors such as the licensing policy, the stringency of price regulation, and the size of the relevant market will affect the patentee to appropriate the social surplus from their inventions.
Price Shock	• Schankerman (1998): A price shock will reduce the value of patent rights in all technology fields.
Patent characteristics	
Number of claims	• Barney (2002), Lowe and Veloso (2006), and Moore (2005): Patent maintenance rates increase with the number of claims.
Claim length	• Barney (2002): Patent maintenance rates generally decrease with claim length.
Length of written specification	• Barney (2002): Patent maintenance rates generally increase with the length of written specification.
Recorded priority claims to related cases	• Barney (2002): Patent maintenance rates generally increase with the number of recorded priority claims to related cases.
Forward citation rates	• Barney (2002) and Moore (2005): Forward citation rates are positively associated with patent maintenance rates. • Thomas (1999): Both self-citations and external citations are positively associated with patent renewal rates. • Serrano (2010): More frequently cited patents are more likely to be renewed. An extra citation decreases the predicted probability of a small innovator patent being allowed to expire at age 13 by about 1 percentage point as compared to the mean of the sample, which decreases from 36.9% to 35.9%.

Table 1.1 (cont.): Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Patent generality	• Serrano (2010): Patents with higher generality are more likely to be renewed.
Trade	• Serrano (2010): The probability of a previously traded patent expiring at any renewal date is lower than that of an untraded patent.
Inventors	• Moore (2005): Expired patents also listed fewer inventors than patents that were maintained. • Liu (2014): Having star inventors on the inventor team, the larger size of the inventor team, the cross-location collaboration of the invention team increases the likelihood that the patent will be renewed.
Ownership	• Lowe and Veloso (2006): There should be a lower renewal rate among patents for whose assignee is not located in U.S. • Moore (2005): Patents that are assigned to corporations are more likely to be maintained than those that are unassigned. • Moore (2005): Foreign companies are more likely to maintain the patent rights due to the high transaction cost rule out foreign companies to file low quality patents. • Thomas (1999): The proportion of assigned patents that go full term is far higher than the proportion of unassigned patents that do so.
Sequential innovations	• Liu, Arthurs, Cullen, and Alexander (2008): A patent that belongs to a sequence of patented innovations is more likely to be renewed.

Table 1.1 (cont.): Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Age	• Serrano (2010): The probability of an active patent being allowed to expire increases with age.
Industry	• Pakes, Simpson, Judd, and Mansfield (1989): The order of the value of patent: pharmaceuticals and other chemical related industries > mechanical industries > electrical industries > low-tech industries. • Schankerman (1998): Pharmaceutical and chemical patents have relative low mean, high dispersion, and slow rate of depreciation. • Moore (2005): Results show that chemical, drugs, and medical industries are less likely to be maintained than mechanical; electrical & electronics; and communica-tions & computer patents, which contradicts the estimation of patent protection value. The explanation is that the pharmaceutical industry usually experiences a patent rush. • Thomas (1999): Patents in technological intense areas, such as data processing and biochemistry, often go full term. For example, electronics often go full term. A slightly lower proportion of pharmaceutical patent goes full term, which is caused by the high costs of clinical trials that are often undertaken before pharmaceutical patents become commercial products.
Firm	
Exploratory	• Lowe and Veloso (2006): Both "new to firm" and "new to science" patents are more likely to be abandoned by the focal firm.

Table 1.2: Outline of the Three Empirical Chapters

Chapters	**Research Questions**	**Dependent Variable(s)**	**Independent Variables**
Chapter 2 – The Impact of Patent Abandonment on Cumulative Inventions	How does the focal firm's patent abandonment decision influence cumulative inventions derived from this abandoned patent?	1. Number of external forward citations (which excludes self-citations) 2. Number of patent classes that are covered in external forward citations.	1. Patent abandonment 2. Year to grant
Chapter 3 – Firms' Patent Abandonments and Subsequent Inventions: Knowledge Spillover Pools, Absorptive Capacity, Open Innovation and Complementary Patents	Under what conditions is a firm more likely to learn successfully from the knowledge spillover pool that is created by its patent abandonment?	Number of patents of the focal firm that are built on patents in knowledge spillover pool after initial patent abandonment.	1. Quality of knowledge spillover pool 2. The focal firm's search path in creating the patent 3. The focal firm's internal usage of the abandoned patent 4. Prior external knowledge sourcing experience 3. Self-owned active complementary patents

Table 1.2 (cont.): Outline of the Three Empirical Chapters

Chapter 4 – Firms' Patent abandonment and Search for Subsequent Inventions: Distant Knowledge, New-to-Firm Inventors and Technological Strength	Which type of patent within the knowledge spillover pool is more likely to be integrated in the focal firm's subsequent inventions?	Is the patent, within the knowledge spillover pool, used in the focal firm's subsequent inventions?	1. Whether the patent assignee is "new-to-firm" assignee 2. Knowledge distance between the recombinant knowledge and the focal firm's existing knowledge base 3. The focal firm's technological strength in area of patent within the knowledge spillover pool

Figure 1.1

Timeline of Patent Renewal and Patent Abandonment

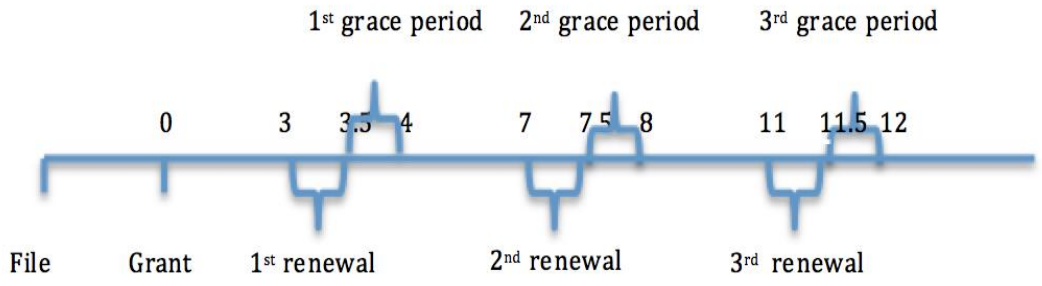


Figure 1.2

The Invention Stages following Patent Abandonment

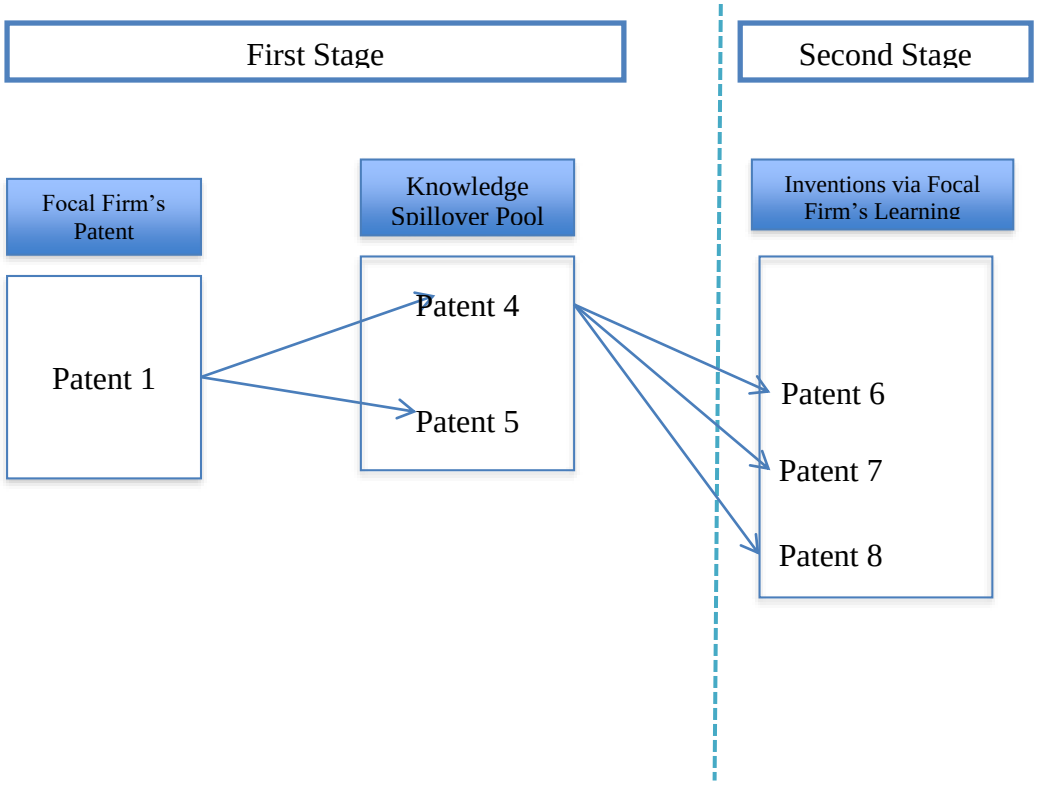


Figure 1.3

Example of the Focal Firm's Sequence of Inventions

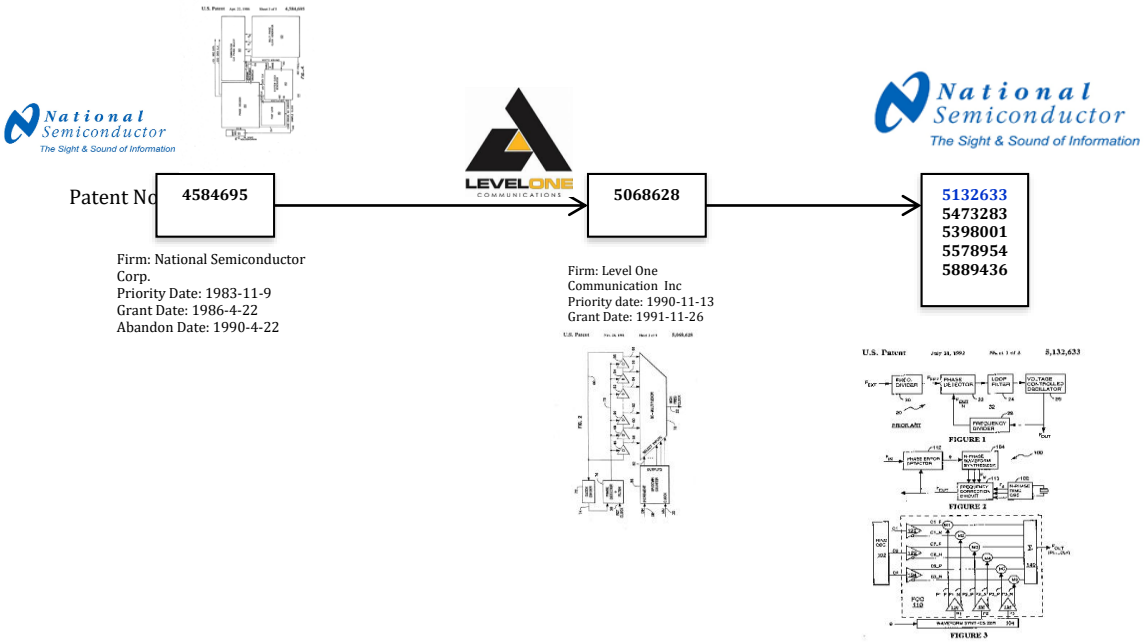


Figure 1.4

Structure of the Dissertation

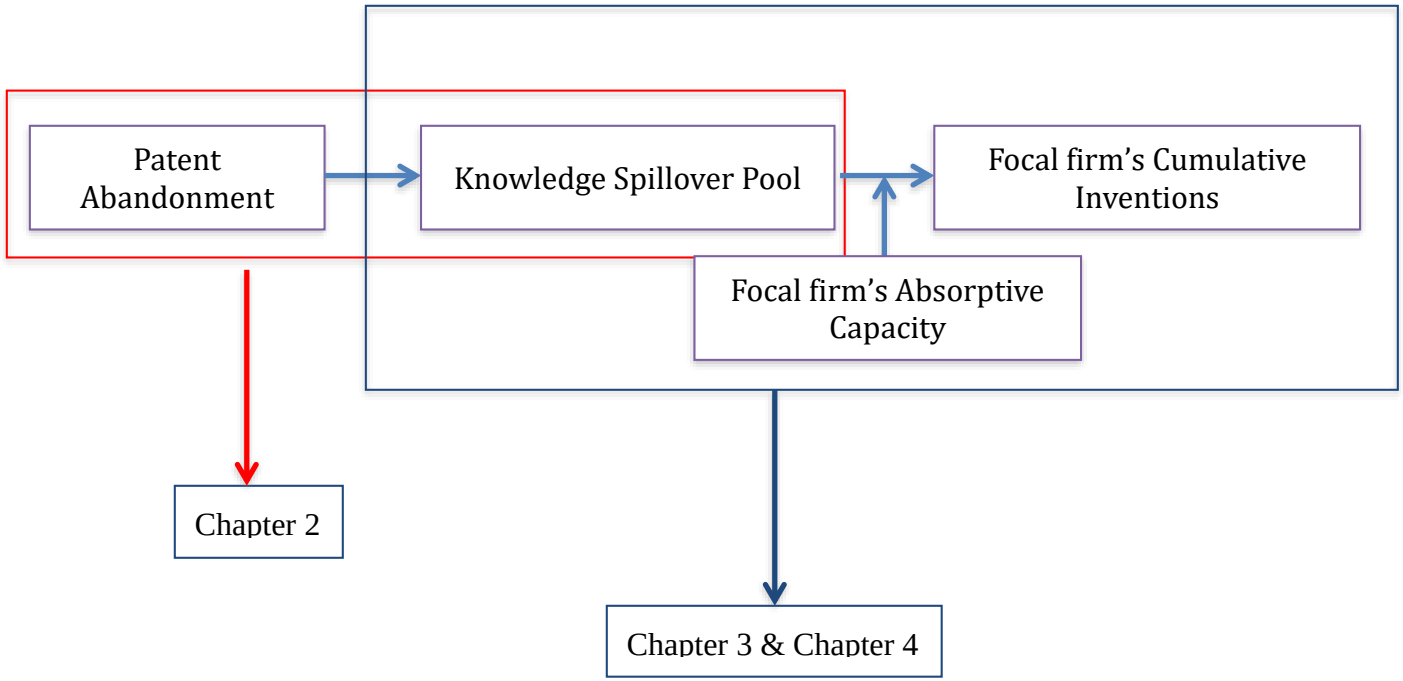
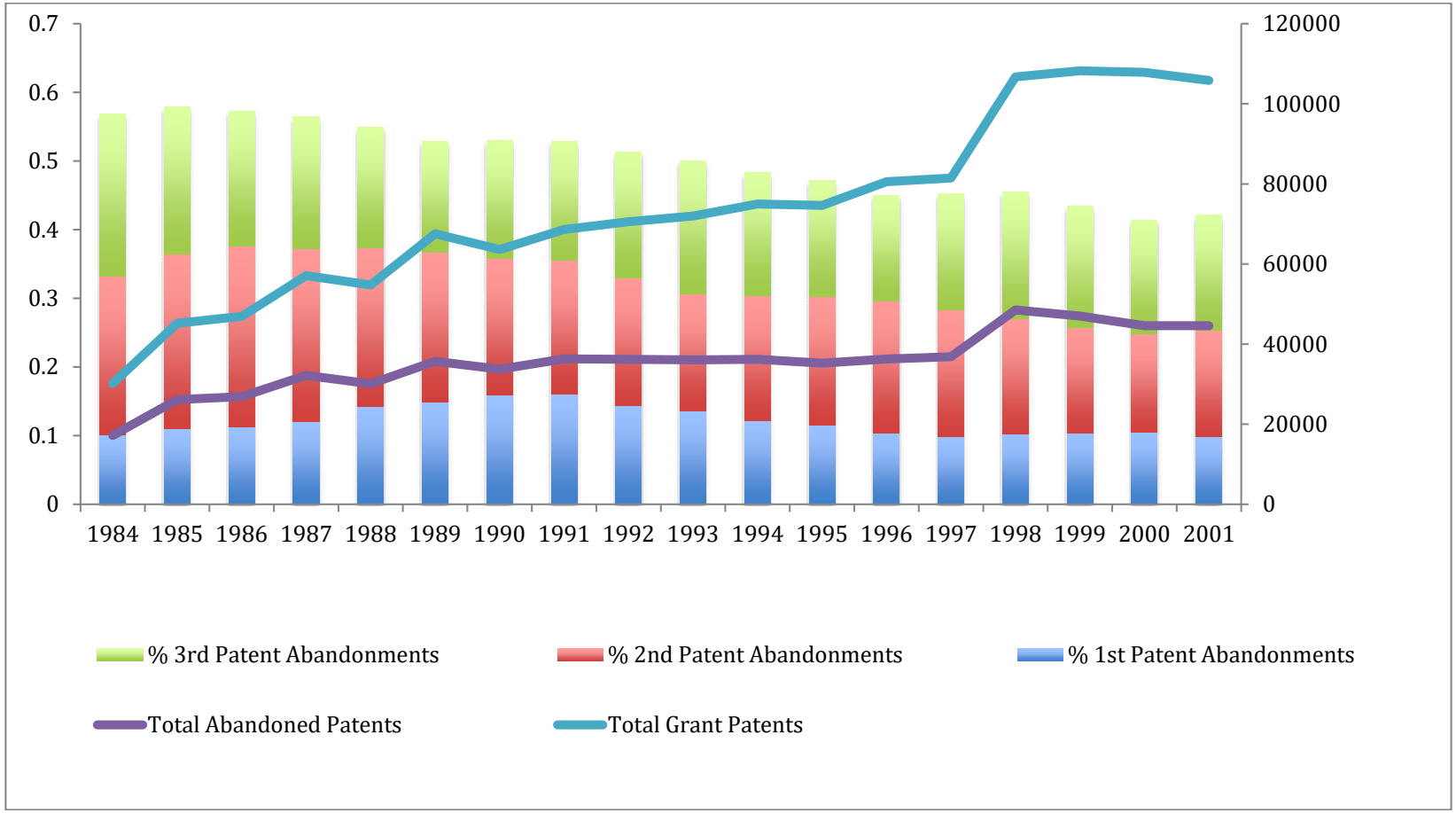


Figure 1.5: Trend of US Patent Abandonment



CHAPTER 2: THE IMPACT OF A FIRM'S PATENT ABANDONMENT ON SUBSEQUENT CUMULATIVE INVENTIONS

2.1 Introduction

As mentioned in Chapter 1, the focal firm is required pay three post-issuance maintenance fees to keep the patent in force. Recent empirical evidence shows that firms abandon about 40% of patents before their regular expiration date (of 20 years after the priority date), based on their decisions to decline paying maintenance fees (Serrano, 2010; Vishnubhakat, 2015). Though there are large numbers of patents abandoned by the focal firm before their full statutory life, the research literature lacks detailed analyses about the impacts of such patent abandonments. Further, innovation becomes cumulative, which means one of the focal firm's invention can have spillover impacts because subsequent inventions may be built on the initial invention. For example, Microsoft Excel is built on Lotus 1-2-3, which in turn is built on VisiCalc. The public policy intent to facilitate such cumulative inventions has been long-standing (Bessen & Maskin, 2009, Kitch, 1977). Facilitating cumulative inventions is especially important when the first invention has little (or even negative) economic value as a stand-alone invention, but is a foundation for valuable subsequent inventions (Scotchmer, 1991). The initial invention cannot realize its full technological or market potential, and thus to create sufficient economic value to the society and the focal firm, if the focal firm and/or external inventors fail to search comprehensively for subsequent development of this invention. Thus, policymakers, when designing a patent system, should consider not only the conventional neoclassical economics tradeoff between innovation and deadweight loss created by monopoly, but also whether the patent system enables or constrains subsequent cumulative inventions (Sampat & Williams, 2015). This chapter seeks to fill the existing research gap and explores how

the focal firm's patent abandonment decision could influence the external inventors' subsequent development of cumulative inventions, which build on the focal firm's abandoned patent.

Existing literature holds that the focal firm usually abandons its patents that it perceives to be potentially less economically valuable (Liu, Arthurs, Cullen, & Alexander, 2008; Pakes, 1986; Serrano, 2010). One rationale for why the focal firm might abandon its patent is because it recognizes its failures in the initial experiment of the technologies (Khanna, Guler, & Nerkar, 2016) and decides to discontinue this technology. The extant literature either applies patent renewal data to estimate the value distribution of the patents (Pakes, 1986), or as a proxy of the private value of the patent (Liu, 2014). However, these studies underestimate the value of patent abandonment because they do not consider the knowledge spillovers that can be created when the focal firm chooses to abandon its patent (Bloom, Schankerman, & Van Reenen, 2005; Harhoff, Scherer, & Vopel, 2003). The focal firm's abandoned patents are no longer enforceable, which mitigates overlapping property rights in the form of patent thickets, and thus the focal firm's patent abandonment may stimulate invention due to lower *ex ante* transaction costs (Mills & Tereskerz, 2011; Ziedonis, 2004). Removal of patent thickets through the focal firm's patent abandonment can generate greater knowledge spillovers and facilitate subsequent cumulative inventions (Galasso & Schankerman, 2015). I seek to extend the extant literature to examine knowledge spillovers that are created by the focal firm's patent abandonment.

This chapter further explores how the focal firm's patent abandonment influences the breadth of subsequent cumulative inventions conducted by external inventors, which is less explored in the existing literature. Currently, academic scholars and practitioners give

more attention to not only the *amount*, but also the *breadth* of subsequent cumulative inventions deriving from the initial patent. According to the resource-based approach, a resource can become more economically valuable when more "services of the resources" are discovered or created (Foss & Foss, 2005; Kim & Mahoney, 2010; Penrose, 1959). Modern technologies are dynamic and often overlap multiple fields and application areas.[5] For example, virtual reality -- a branch of computer technology -- has applications in several major industries including the military, health care, and entertainment industries. Thus, the focal firm should search broadly and explore more the usability of its patents. If the focal firm holds the patent to have exclusive rights over the use of its technology, it is more likely to restrict its attention within its familiar area (Cyert & March, 1963; Ocasio, 1997) and conduct intelligent searches where its routines, cognitive framing, and absorptive capacity enable its effective assessment of alternatives and consequences (Afuah & Tucci, 2012; Cohen & Levinthal, 1990). However, to realize more of its market and technological value, the focal firm might need to recombine its patent with knowledge that is located distant from the focal firm's existing knowledge base. The focal firm's bounded rationality and the potential high cost of conducting distant search might impede it to search broadly for the exploration and exploitation of its patent. After the focal firm abandons its patent, the potential external inventors with relevant knowledge (which might be located distant from the focal firm's existing knowledge base) can be self-motivated to conduct subsequent cumulative inventions that build on the focal firm's abandoned patent. The focal firm's patent abandonment can transform its limited internal search into broader

[5] See https://www.greyb.com/patent-portfolio-strategy-filing-patent-continuations/

external inventors' collective search. Consequently, the cumulative inventions conducted by external inventors can also become broader after the focal firm's patent abandonment.

This chapter seeks to contribute to the debate on whether intellectual property rights will foster or hinder cumulative inventions, not just from the perspective of the amount of cumulative inventions, but also from the breadth of cumulative inventions. On the one hand, the literature holds that the patent system increases inventions both from the original inventor and from follow-on inventors by providing monopoly power to the original inventor and serving as coordination mechanisms for subsequent inventors (Bessen & Maskin, 2009; Galasso & Schankerman, 2015; Kitch, 1977; Scotchmer, 1991). On the other hand, "anti-commons" theory suggests that the original inventor's patent might block external follow-on inventors from conducting subsequent inventions derived from that initial patent. This anti-commons effect may occur due to the high transaction costs for these follow-on inventors to get access to that initial patent, which is required for them to develop subsequent cumulative inventions (Heller & Eisenberg, 1998).

While some empirical research corroborates the "anti-commons" effect by showing that patents could significantly reduce cumulative inventions (Murray & Stern, 2007; Williams, 2013), other research studies find little empirical evidence for the anti-commons effect of a patent (Hall & Helmers, 2013; Sampat & Williams, 2015). The current chapter provides further evidence in the context of patent renewal and abandon-ment. Mills and Tereskerz (2011) maintain that concerns with human gene patents blocking subsequent inventions should not be considered as serious as originally anticipated due to a declining renewal rate of patents, which thus reduces patent thickets and can facilitate subsequent invention. Mills and Tereskerz (2011), however, do not analyze whether the focal firm's

patent abandonment would lead to a net increase or a net decrease in subsequent cumulative inventions. Therefore, building on previous research studies, this chapter provides further examination of the "anti-commons" effect by comparing the amount and the breadth of cumulative inventions that build on the abandoned patents relative to that built on renewed patents.

2.2 Literature review

There are debates concerning the impact of a patent on cumulative inventions. Conventional economic wisdom holds that the patent system increases inventions because a patent can provide the original inventors monopoly power and protects them from competitors' imitation of the original invention, thereby encouraging more R&D investment by the focal firm as the original inventor (Kitch, 1977; Scotchmer, 1991). Besides enabling the focal firm to secure monopoly power and to recoup its R&D costs, some patents also encourage inventions on the part of follower-on inventors who would otherwise be inclined to imitate (Bessen & Maskin, 2009). Further, the focal firm's initial patent can act as a gatekeeper to coordinate subsequent inventions, which would be impeded by coordination failure and free riding among follow-on inventors without the coordination of a focal firm's initial patent (Galasso & Schankerman, 2015; Kitch, 1977).

However, recent analytical and empirical studies show a negative impact of the focal firm's patent protection on subsequent cumulative inventions. When subsequent inventions build on preceding ones, strong patent protection for the focal firm's initial patent provides poor incentives to conduct subsequent cumulative inventions for both the focal firm's inventors and external inventors (Bessen & Maskin, 2009; Scotchmer, 1991).

For the focal firm as the original inventor, a patent provides a delay option for conducting subsequent inventions, due to a reduction in competitive pressures. The focal firm may thus allocate more of its resources from conducting subsequent inventions to litigation activities (Smeets, 2014). Even though the focal firm would like to allocate sufficient resources to develop the invention, its search in exploration and exploitation of its patent is posited to be limited, and restricted to narrow areas due to its bounded rationality and high costs of conducting distant search. In addition, to use the interfirm collaboration activities to develop subsequent inventions, the focal firm needs to identify potential subsequent inventors, who are aware, motivated, and capable of further developing the focal firm's initial patent (Chen, 1996). However, sometimes, such inter-firm collaboration activities might create high transactions costs caused by high information asymmetry and high uncertainty, high coordination costs, and potential external inventor's unwillingness to collaborate (Alexy, George, & Salter, 2013). If the focal firm lacks sufficient resources and capabilities, it is less readily positioned to cover these high transaction costs, which can lead to an underinvestment of subsequent inventions by the focal firm through the traditional mode of collaboration (such as licensing and strategic alliance) (Alexy, George, & Salter, 2013; Heller & Eisenberg, 1998).

Potential follow-on inventors usually need to negotiate contract terms over the initial patent with the focal firm to conduct subsequent inventions built on the focal firm's initial patent. From an "anti-commons" perspective, the focal firm's expansion of its initial patent will increase the transaction costs of the potential follow-on inventors using the market for technology to conduct follow-on research, which leads to an under-use of knowledge that is the result of the (over-) protected initial patent (Heller & Eisenberg,

1998, Huang & Murray, 2009; Ziedonis, 2004). Heller and Eisenberg (1998) suggest two mechanisms that might lead to an "anti-commons" effect. First, when the ownership of the upstream patents, which would be needed by the follow-on inventors to conduct subsequent research, is fragmented, these follow-on inventors would incur higher transaction costs because it must now negotiate multiple license agreements with many different patent holders. The uncoordinated bargaining among these multiple exchange parties leads to "royalty stacking," which reduces the follow-on inventors' economic rents and leads to an underinvestment in subsequent inventions that have the potential for commercialization success (Galasso & Schankerman, 2015; Heller & Eisenberg, 1998). Second, stack licensing makes it difficult for potential follow-on inventors to establish clear boundaries to their respective property rights, and this overlapping of property rights can lead to an "anti-commons" effect. In this case, when the outcome of the development of the focal firm's initial patent is uncertain and the potential gains for the follow-on inventors are speculative, it is not clear whether the value for these subsequent inventors can overcome the "anti-commons" effect, and thus can stifle cumulative inventions. Heller and Eisenberg (1998) also propose that an "anti-commons" effect in biomedical research may be more likely to endure than in other technology areas because of the high transaction costs of bargaining, heterogeneous interests among owners, and the cognitive biases of bio-pharmaceutical researchers. Table 2.1 provides a literature review on the "anti-commons" literature.

When the focal firm lacks the resources and capabilities to develop the inventions internally, and the transaction costs of employing a traditional collaboration mode to further develop the initial patent are high for the focal firm and potential follow-on inventors, the focal firm can facilitate subsequent inventions through abandoning its

intellectual property rights (Alexy, George, & Salter, 2013). This chapter builds on "anti-commons" theory and examines whether the focal firm's patent abandonment can facilitate cumulative inventions conducted by potential external follow-on inventors.

Empirical research studies are mixed concerning the existence of an "anti-commons" effect. Murray and Stern (2007) apply the existence of a patent grant lag in the United States and conduct difference-in-differences estimation to corroborate a modest "anti-commons" effect by showing the citation rate to papers that are paired with a patent declines by approximately 10 to 20 percent after the patent is granted. As an extension, Huang and Murray (2009) show that patents with: (i) a more complex ownership structure; (ii) in a fragmented market; (iii) broad scope; and (iv) strong protection will intensify the "anti-commons" effect of the patent. Williams (2013) applies data on the sequencing of the human genome by the public Human Genome Project and private firm Celera to estimate the impact of Celera's gene-level patents on subsequent innovation. Across a range of empirical specifications, Williams (2013) finds evidence that Celera's IP led to reductions in subsequent scientific research and product development on the order of 20 to 30 percent. Murray and colleagues (2010) find a significant increase in both the amount and diversity of follow-on research using the related patents after NIH-MoU, which is an agreement signed between NIH and DuPont to open up two genetic modification technologies (i.e., Cre-lox and Onco).

Galasso and Schankerman (2015) propose that whether the focal firm's initial patent enables or constrains subsequent inventions depends on the tradeoff between the *ex-ante* bargaining failure between the focal firm and the subsequent inventors, and the *ex-post* coordination failure among the subsequent inventors. This study applies the random

allocation of judges at the U.S. Courts of Appeals for the Federal Circuit as instrument variables and corroborates that the removal of patent rights through courts invalidation leads to a 50% increase, on average, in citations to the focal firm's invalidated patent. Further, it shows that the impact of patent invalidation is more statistically significant and economically substantive when the market is fragmented and complex and is largely driven by the impact of patent invalidation from the larger firms. Unlike most of the previous research studies, which focuses on the biomedical industry, Galasso and Schankerman (2015) conduct a cross-industries study, showing that the impact is heterogeneous across industries: a focal firm's initial patent significantly blocks subsequent inventions in the computer, electronics, and medical instruments industries, but not in drugs, chemicals, or mechanical technologies. In terms of biomedical industry, the "anti-commons" effect is statistically significant and economically substantive in the medical instruments industry, while not so in the drug industry.

Wen and colleagues (2016) examine whether, and under what conditions, IBM's announcements of non-assertion of patents against the open source software (OSS) community, and the creation of the patent commons (a specific set of patents that were made available royalty free to the OSS community under certain conditions) affect the entry of new products issued under an OSS license by U.S. software start-up firms. The results show that a 10% increase in The Commons' patent claims in a software market is associated with an average 1% to 3% increase in the rate of OSS entry by start-ups into that market. Further, the impact of such IP strategy is predicted to have a greater impact on OSS entry when innovations are cumulative and when IPR ownership is highly concentrated. Contrary to conventional "anti-commons" prediction, Wen and colleagues

(2016) show that fragmentation of ownership of the upstream patents (of the subsequent inventions) negatively moderates the relationship of upstream patent protection on subsequent cumulative inventions. Conventional "anti-commons" theory focuses on the licensing costs of obtaining fragmented patent rights, Wen and colleagues (2016) examine another effect of ownership fragmentation. Fragmentation of patent ownership decreases the economic value of the negotiation for patent holders, resulting in a decrease in the focal firm's incentives to litigate. Galasso and Schankerman (2011) show both theoretically and empirically that when patent ownership is fragmented, the settlement of the patent lawsuit by the focal firm can be faster. Thus, the expected cost of infringement to the subsequent inventors is lower when the ownership is more fragmented.

While the above research literature provides largely supportive empirical evidence for the "anti-commons" effect, there are also research studies that do not corroborate the blocking effect of patents. For example, Hall and Helmers (2013) examine how the firms' donations of their patents to the "Eco-patent pool"[6] will affect the diffusion of green technology. Employing a research design that is similar to difference-in-differences, this study shows that providing their patents to all third parties royalty-free has no discernible impact on the diffusion of the knowledge embedded in the protected technologies. However, given the short time-period available in the study, the results cannot fully establish that the patent has had a statistically insignificant effect on the diffusion of the invention.

[6] A number of large firms such as Sony, IBM, Nokia, and so forth, claim to address the problems that patents might cause in environmental protection through the creation of an "Eco-Patent Commons," together with World Business Council for sustainable development. Firms pledging patents to this commons are required to sign a non-assertion pledge that allows third parties to have royalty-free access to the protected technologies (Hall & Helmers, 2013).

Sampat and Williams (2015) design two quasi-experimental methods to show how a human gene-related patent would affect follow-on inventions in terms of scientific research & innovative product commercialization. First, this study presents a comparison of follow-on inventions across genes that are claimed in accepted versus rejected patent applications. Second, to control for endogeneity in the quality of accepted and rejected patents, this study applies the construct of "leniency" of the assigned patent examiner as an instrumental variable. Both empirical estimations show that, on average, gene patents have not had quantitatively important effects on follow-on innovation. The results seem to conflict with previous empirical research showing at least modest "anti-common" effects of gene-related patents (Huang & Murray, 2009; Murray & Stern, 2007; Williams, 2013). To explain these different results, Sampat and Williams (2015) suggest that the "anti-commons" effect exists because a patent provides limited access to knowledge and technology embedded within that patent, which leads to high transaction costs when gaining access to knowledge and technology within the patent. However, gene-related patents retain open access to academic researchers. The "tolerated infringement" within this context is a common feature of the use of patented knowledge and technology by academic researchers. In this perspective, a patent does not restrict inventors' access to knowledge and technology in the patent and thus will not generate as high transaction costs in licensing markets. Thus, patents will not deter subsequent cumulative inventions.

Table 2.2 summarizes the extant empirical literature on how patents influence subsequent cumulative invention.

The literature also proposes an alternative explanation about why gene patents do not present "anti-common" effects, as this theory would have us expect. Mills and

Tereskerz (2011) show that though there are large amounts of gene patents that can create patent thickets and that block subsequent cumulative innovation, patent holders do not renew all the gene patents over time. If these patent holders abandon their patents, then these patents are no longer enforceable and so would not contribute to a patent thicket. Consequently, because of the declining rate of patent renewal, "the concerns with gene patents blocking subsequent innovation may not be as serious as originally anticipated (Mills & Tereskerz, 2011: 712). Building on Mills and Tereskerz (2011), I explore whether the focal firm's patent abandonment can address the patent thickets problem and has any positive impact on the diffusion of technology concerning this abandoned patent. Similar to Galasso and Schankerman (2015), this chapter conducts cross-industries analysis, which further examines whether the mechanism proposed by Mills and Tereskerz (2011) can be generalized across industries.

2.3 Development of Hypotheses

Patent abandonment and subsequent cumulative invention

Modern inventions typically are outcomes of open and cumulative inventions, which involve multiple inventors conducting subsequent research that builds on the original invention to bring it to an innovative commercialization (Alexy, George, & Salter, 2013; Chesbrough, 2003; Nelson & Winter, 1982). Due to the focal firm's bounded rationality, its search for exploration and exploitation of its innovation is posited to be bounded. That is, it is more likely to restrict its attention within its familiar area (Cyert & March, 1963; Ocasio, 1997) and conduct intelligent searches where its routines, cognitive framing, and absorptive capacity enable its effective assessment of alternatives and consequences (Afuah & Tucci, 2012; Cohen & Levinthal, 1990). Consequently, to realize

more market and technological value of the focal firm's patent, the focal firm, instead of conducting all the subsequent research and development internally, needs to collaborate with potential external follow-on inventors.

In many cases, the focal firm's holding of an initial patent can make it difficult to collaborate with potential external inventors who might be capable of collectively searching for subsequent development of the initial invention into more valuable innovation. For the focal firm as the technology provider, it can collaborate with the external inventors through licensing or strategic alliance to develop further the initial patent. The focal firm's holding of a strong patent can facilitate collaboration by reducing coordination costs and mitigating misappropriation risks in a traditional collaboration mode (Arora & Ceccagnoli, 2006). However, these traditional modes of collaboration are not always efficient and effective for facilitating subsequent cumulative inventions. For example, high information asymmetry and high uncertainty increase the focal firm's cost of searching and identifying potential technology buyers in the market for technology (Ziegler, Gassman, & Friesike, 2014). Even if the focal firm can find effective exchange partners for technology development, these potential partners might be unwilling to coordinate and cooperate with the focal firm due to divergent interest among partners (Alexy, George, & Salter, 2013). When the costs of using these traditional collaboration modes outweigh the benefit of the subsequent inventions brought to the focal firm, the focal firm will not seek to collaborate with external inventors to develop further the technology in the patent. Instead, the focal firm might put the invention into the "shelf" without further development of its patent. Further, the traditional mode of collaboration is usually under the shadow of contracts. Under certain circumstances, the contract term itself might impede external inventors in

conducting subsequent inventions built on the initial patent. For example, considering the potential "boomerang effect,"[7] the focal firm would usually include a "grant-back clause"[8] in the licensing agreement, which impedes the technology buyer's subsequent inventions built on the focal firm's initial patent (Leone & Reichstein, 2012). In addition, the licensor typically includes the "exclusivity" term in the licensing contract to provide safeguards for a licensee's further development (Somaya, Kim, & Vonortas, 2011).

From the perspective of external inventors (technology acquirers), they are often required to negotiate a contract over the initial patent with the focal firm to continue the development of the initial patent (Ziedonis, 2004).[9] When the subsequent inventions must build on multiple patents owned by several patent holders, the external inventors conducting subsequent inventions must bargain with several patent holders, which increases transaction costs (Ziedonis, 2004). Moreover, when the external inventors are capital constrained, the cost of collaborating with the focal firm to develop this focal firm's initial patent would be even higher. For example, the external inventors lacking in bargaining power usually need to pay a premium when licensing-in technologies from technology providers, which might be an obstacle for capital-constrained firms (Ozmel,

[7] According to Choi (2002), the "boomerang effect" refers to granting others the rights to use its intellectual property may enable them to develop new products, which make the licensed technology obsolete and leave the licensor in the backwater of technology.

[8] License agreements often include a grant back clause, which obligates licensees to grant the licensor the rights to further advances or improvements to the licensed technology developed during the term of the agreement.

[9] The U.S. patent law is a unitary system, which means the system grants the patent holder the temporary rights to use the technology exclusively, but it does not allow the patent holder to use technologies in other patents during a limited time (Ziedonis, 2004). In other words, if a firm independently makes an invention that can be used to improve or develop the technology in a certain patent, it might infringe on the patent rights of that initial patent holder. To continue this development, this firm needs to negotiate a contract over the initial patent with the patent holder.

Robinson, & Stuart, 2013). In addition, capital-constrained follow-on inventors usually need to relinquish some control rights over subsequent inventions when forming strategic alliances with large firms. The commitments by these follow-on inventors in the early stages of their development would constrain their later expansion (Argyres & Liebeskind, 2002). The high costs lead to an underinvestment in further developing that initial patent. Thus, instead of using the technology in the initial patent, external inventors will choose to invent around or employ a substitute technology, which is less protected, for their subsequent inventions.

Overall, the focal firm's holding of a strong initial patent might discourage the potential follow-on inventors to conduct subsequent research that builds on the focal firm's initial patent. In this situation, consistent with anti-commons theory (Heller & Eisenberg, 1998; Ziedonis, 2004) emphasized in this chapter, the focal firm can facilitate subsequent cumulative invention by abandoning its patent through the decision to decline paying the maintenance fees required by USPTO. As mentioned in chapter 1, the patent becomes available in the public domain to be practiced and improved upon after the focal firm abandons this patent. For follow-on inventors, the cost of using, developing, and improving the knowledge and technologies in this patent is reduced significantly. While the focal firm can reinstate the patent that had been abandoned, the reinstated patent does not have the same strength as the initial patent. The follow-on inventors are permitted to acquire the intervening rights,[10] which allow these follow-on inventors to continue using the patent

[10] Intervening rights in reinstated patents are provided by 35 U.S.C. 41(c) (2) which is reproduced in MPEP 2501. No patent, the term of which has been maintained as a result of the acceptance of a late payment of a maintenance fee, shall abridge or affect the right of any person or his or her successor in business who made, purchased, imported, or used after the 6-month grace period but prior to the acceptance of the late maintenance fee anything protected by the patent, to continue the

even after the initial patent is successfully reinstated. Further, a patent that had lapsed and was then reinstated opens the door to attacks from potential follow-on inventors that would not be available if the patent had never been abandoned. For example, follow-on inventors might argue that a focal firm's reinstated patent is invalid.

The focal firm abandons the patent because holding the patent is not expected to create sufficient economic value to cover the costs of maintaining it. However, due to the reduction costs of using, developing and improving upon the abandoned patent, the focal firm's abandoned patent can provide opportunities for external inventors with relevant resources and capabilities to conduct subsequent inventions built on the abandoned patent (Cassiman & Ueda, 2006); as is shown by the following:

> *The upside of [an] abandoned patent is that the inventions [it] describes enter the public domain prematurely, on abandonment rather than 20 years from filing, and [it] can allow outside parties to leverage cutting-edge research from leading labs. Accordingly, some of the patents abandoned by large companies may nonetheless be very valuable for small enterprises.*
>
> - Yali Friedman (founder of DrugPatentWatch.com)[11]

> *I have written before that about 50% [of] patents expire prematurely because the patent owners choose to not pay the maintenance fees. In many ways, this is a good thing in that it clears-the-desk of patents whose owner may know of their [being] worthless but that still require analysis and consideration by anyone conducting a freedom-to-operate search.*
>
> - Dennis Crouch (Law professor at the University of Missouri, School of Law)[12]

use or importation of, or to sell to others to be used or sold, the specific things made, purchased, imported or used.

[11] See http://www.biotechblog.com/2015/01/12/patentdrop-com-posts-public-domain-inventions/

[12] See http://patentlyo.com/patent/2012/09/patent-maintenance-fees.html

Consequently, anti-commons theory suggests that there might be more subsequent inventions building on the focal firm's initial abandoned patent relative to the case in which the focal firm renewed the patent. In line with a growing number of economics and management research studies (Chan, 2014; Galasso & Schankerman, 2015; Jaffe, Trajtenberg, & Fogarty, 1993), I use forward citations to identify knowledge spillovers and cumulative inventions. According to U.S. patent law, a patent applicant must cite prior work/art of the same subject to demonstrate the advancement of his/her technology. In empirical settings, the citation link from one patent to another permits (albeit incompletely) linking one generation of knowledge production to the next (Trajtenberg, Henderson, & Jaffe, 1997). Moreover, the expiration of a patent has no impact on its prior art status (35 U.S. code, section 102), so that the requirement to cite it remains in place (Galasso & Schankerman, 2015). This logic leads to the following hypothesis:

H1: Ceteris Paribus, a focal firm's patent will receive more external forward citations when abandoned than when renewed.

Innovation is typically defined as "the process by which existing knowledge and inputs are creatively and efficiently recombined to create valuable outputs" (Felin & Zenger, 2014: 915; Schumpeter, 1934). When exploring the full economic potential of its patent, the focal firm needs to search knowledge either from its own knowledge base or from external inventors' knowledge bases and to recombine this new knowledge with the existing knowledge embedded in this initial patent. The focal firm can either search knowledge for subsequent development of its inventions internally, or cooperate with some external inventors in developing cumulative inventions. In both mechanisms, the focal firm tends to search locally for knowledge within its current technological domain (Helfat, 1994), which is influenced by its routines, cognitive frame, and absorptive capacity. The

costs of distant search are usually high because it requires the focal firm to acquire new resources and capabilities (Afuah & Tucci, 2012).

With internal development, companies are relatively well-coordinated environments for amassing and marshalling specialized knowledge to explore opportunities for invention. Companies operate on traditional incentives (namely salary and bonus) and employees are assigned clearly delineated roles and specific responsibilities, which discourages them from seeking challenges outsides their purview (Boudreau & Lakhani, 2014). When cooperating with external inventors, the focal firm first needs to possess the capabilities to identify and evaluate potential external inventors with relevant knowledge, which is also restricted by the focal firm's knowledge, experiences, and absorptive capacity. A substantial difficulty of achieving invention arises when managers are unaware of the location of relevant knowledge (Felin & Zenger, 2014). Further, the focal firm needs to negotiate an *ex ante* contract with potential external inventors, which might entail high transaction costs due to incomplete contracting problems (Williamson, 1985). The cost will be even higher for the focal firm when contracting with external inventors in an unfamiliar domain. Further, some contract terms, such as "grant-back" clause and exclusivity, might also limit the breadth of inventions by external inventors. Overall, the boundedly rational focal firm that develops subsequent inventions usually concentrates in narrowly specified areas either through internal or external development.

Once the patent is abandoned by the focal firm, it becomes available in the public domain and free to be practiced upon by external inventors. The widely diverse external inventors with varied skills, experiences, and perspectives are posited to self-select to develop the subsequent inventions according to their knowledge base. The scale and

diversity of the crowd transforms the focal firm's distant search to some external inventor's local search, thereby improving the efficiency and effectiveness of cumulative inventions. Thus, the subsequent inventions tend to be widely distributed and involve knowledge that is far from the focal firm's original knowledge base.

H2: Ceteris Paribus, a focal firm's patent will receive external forward citations with greater breadth when abandoned than when renewed.

2.4 Methodology

Data and Sample

The empirical work is based on two datasets. First, I collect patent renewal and abandonment data from *USPTO Official Gazette*, which lists expired patents weekly. Second, I obtain patent level data from *NBER patent dataset*. To make the two datasets comparable, I keep the patents that are granted between 1984 and 2001.[13] Following Galasso and Schankerman (2015), I conduct cross-industry analyses. I identify 1,330,983 patents in the final sample, in which 158,805 patents are abandoned in the 4th year, 1,168,096 are renewed in the 4th year, and 4,082 are abandoned in the 4th year but later reinstated by the focal firm.[14]

Dependent Variables

In line with previous research, I use the number of *external forward citations* (*EFC*) of the focal firm's abandoned patent to measure the amount of subsequent cumulative inventions conducted by the follow-on inventors. I use the number of patent classes that

[13] The two datasets have more overlap in these time-periods.

[14] For robustness check, I examine the effect of 2nd (8th year to grant) and 3rd (12th year to grant) patent renewal and abandonment in the additional analysis section. However, the difference of the effect among different renewal sample is not within the scope of the current chapter.

are covered in theses external forward citations to measure the breadth of subsequent cumulative inventions. *EFC* is measured as the count of the external citations (total citations minus the self-citations) the patent has received annually. I exclude self-citations because they can be endogenous in the sense that the focal firm would reduce the internal citations of the patent in expectation of the future patent abandonment. In addition, I adjust both the amount and the breadth of the external citations by dividing the average number and breadth of external citations by all patents in given year. For robust-ness checks, I also examine 2-year, 3-year, and 4-year average external forward citations.

Independent Variables

The construct of *Abandon* is measured as a binary variable, which equals 1 if the patent is abandoned in the 4^{th} year and 0, otherwise. The construct of *Post* is assigned as 1 for the post-abandonment (or post-renewal) period, and zero otherwise.

Control Variables

I include patent and firm-level controls that could potentially influence the external forward citations of the focal firm's initial patent. In each of the econometric models, I also include year- and industry-dummies to control for institutional factors.

Patent-level controls

Patent-level controls include patent *prior forward citations, strength, assignee, scope,* and *originality*. The construct of *Prior forward citations* is used to proxy the patent value before the renewal and abandonment decisions are made. I measure it as the total amount of forward citations before the patent is abandoned. *Strength* is measured as the number of claims that a patent contains. Patents containing more claims are more likely to generate more forward citations (Harhoff & Reitzig, 2004*). Assignee*, which is the number

of assignees for the patent, captures the difficulties of contracting over the focal firm's initial patent. More assignees introduce complexity to licensing and add time to transfer the knowledge when the patent exists (Markman, Gianiodis, Phan, & Balkin, 2005), which thus hinders subsequent innovations built on the patent. *Scope* is measured as the number of international patent classes that is listed in the patent (Huang & Murray, 2009; Lerner, 1995). Broader patents are often more economically valuable to the firm, but are more likely to deter follow-on invention (Bessen & Maskin, 2009; Scotchmer, 1991). I use NBER data on patent *originality* to measure the newest of the patents.

Firm-level controls

Firm-level controls include *diversification, technology focus,* and *size. Diversification* is measured as an adjusted Herfindahl-type index:

$$Diversification_{it} = [1 - \sum_{j} \left(\frac{N_{jit}}{N_{it}}\right)^2] \times \frac{N_{it}}{N_{it} - 1}$$

where N_{jit} represents the number of patents of patent class j in firm i's patent stock at year t. N_{it} represents the total number of patents that are in firm i's patent stock at year t. *Technology focus* reflects the technological strength that the focal firm has on the each of the fields of the focal firm's (abandoned or renewed) patent. I measure *Technology focus* as the percentage of patents in the focal firm's patent portfolio that are in the area of the abandoned patent. *Size* is a dummy variable, which equals 1 if the assignee of the patent is small entity. The data are from *USPTO Official Gazette.*[15]

[15] There are two criteria for small entity: (1) the number of employees, including affiliates, does not exceed 500 persons; and (2) it has not assigned, granted, conveyed, or licensed (and is under no obligation to do so) any rights in the invention to any person who made it and could not be classified as an independent inventor, or to any concern which would not qualify as a non-profit organization or a small business concern under this section. Based on the USPTO, small entities need to pay the patent acquisition and maintenance fees half of the large entities.

Empirical estimation

I conduct a difference-in-differences approach to examine whether there are differences in subsequent cumulative inventions between patents that are renewed and abandoned by the focal firm in the 4th year after issuance of the patent. I also conduct Coarsened Exact Match (CEM) based on application year, grant year, technology field and forward citations before the patent is abandoned. The basic model specification is as follows:

$$
\begin{aligned}
&Log\ (\#\ of\ EFC_{i,j,t} + 1) \\
&\quad = f\big(\epsilon_{i,t};\ \alpha\ Post_t + \beta Abandon_i + \boldsymbol{\varphi Post_t * Abandon_i} \\
&\quad + \zeta Prior\ foward\ citations_i + \delta Backward\ Citations_i + \eta Strength_i \\
&\quad + \mu Scope_i + \chi No.Assignee_i + \psi Originality_i + \mu Generality_i \\
&\quad + \theta Diversification_{jt\_abandonyear} + \delta Technology\ Focus_{jt\_abandonyear} \\
&\quad + \omega Small\ entity_j + Year\ fixed\ effect + Technology\ field\ fixed\ effect \\
&\quad + appyearfixed\ effect\big)
\end{aligned}
$$

$$
\begin{aligned}
&Log\ (\#\ of\ Patent\ Class_{i,j,t} + 1) \\
&\quad = f\big(\epsilon_{i,t};\ \alpha\ Post_t + \beta Abandon_i + \boldsymbol{\varphi Post_t * Abandon_i} + \zeta Prior\ foward\ citations_i \\
&\quad + \delta Backward\ Citations_i + \eta Strength_i + \mu Scope_i + \chi No.Assignee_i \\
&\quad + \psi Originality_i + \mu Generality_i + \theta Diversification_{jt\_abandonyear} \\
&\quad + \delta Technology\ Focus_{jt\_abandonyear} + \omega Small\ entity_j + Year\ fixed\ effect \\
&\quad + Technology\ field\ fixed\ effect + appyearfixed\ effect\big)
\end{aligned}
$$

Results and Discussions

Table 2.3(1) and Table 2.3(2) present some summary statistics for the sample and the subsample (renewed, abandoned, reinstated patents, and all patents). Table 2.4 provides the regression results of our difference-in-differences approach. Model (1) and Model (2) apply *EFC* as the dependent variable, and Model (3) and Model (4) apply *Breadth* as the dependent variable. For comparability to other empirical studies in the literature, a log-linear specification is estimated. To avoid the problem of never-cited patents, research studies usually transform the dependent variable by adding one before taking the log

(Galasso & Schankerman, 2015; Murray & Stern, 2007). Model (1) and Model (3) present results of basic difference-in-differences model. Model (2) and Model (4) present results of difference-in-differences model after conducting CEM based on application year, grant year, technology field, pre-decision external citations, pre-decision internal citations, and the focal firm's *SIC*. This matching cannot address all selection bias problems, but it can mitigate the problem based on some observable factors.

Across all four models, the coefficient of Post*Abandon is statistically significant and positive. The empirical results might be substantially biased by the renewal sample selection effect (Serrano, 2010). A firm's decision to abandon its patent is not random. It is more likely to abandon patents that are potentially less economically valuable. On average, patents renewed will receive more annual forward citations than those abandoned (Harhoff, Scherer, & Vopel, 2003). Therefore, I expect that the existence of a selection effect will underestimate the impact of patent abandonment on subsequent cumulative inventions. Thus, Hypothesis 1 and Hypothesis 2 are corroborated that the focal firm's initial patent will receive both a higher amount and a greater breadth of forward citations when abandoned than when renewed by the focal firm.

Additional Analyses

First, I examine the effect of the 2nd and 3rd patent renewal and abandonment on the number of external forward citations based on the same estimation model. The results, shown in Table 2.5, are consistent with those based on the 1st patent renewal and abandonment. Further, the results show that the effects of patent abandonment on both the amount and the breadth external inventors' cumulative inventions are strongest in the 2nd window of abandonment. Future research can examine further such differences in detail.

Second, to examine whether the treatment effect only happens when the patent is renewed/or abandoned in year 4, I compare the differences of annual external forward citations of renewed and abandoned patents from year 1 to year 8 after they are granted. The empirical results show that before year 4, when the decision of renewal and abandonment should be made, renewed patents received more external forward citations than abandoned patents. However, after year 4, on average, renewed patents receive less external forward citations than abandoned patents. Further, I create the graph to show how the marginal effect of patent abandonment on external forward citations change over Year-to-Grant (see Figure 2.1). The graph shows that the external forward citations of renewed and abandoned patents reveal different trends after year 4, when the focal firm decides whether to renew and abandon the patent.

Third, I conduct the same estimation based on dependent variables of 2-years, 3-years, and 4-years average forward citations. The results are shown in Table 2.7. All of these Tables provide robust results.

Fourth, I conduct the same estimation by including the self-citations in the dependent variable. In the main analysis, I exclude the self-citations due to the endogeneity concern. The empirical findings shown in Table 2.8 provide robust results. The coefficient is larger compared to the results excluding the self-citations. These results provide some evidence that while the focal firm's patent abandonment could increase cumulative inventions from external inventors, the focal firm could also increase its own cumulative inventions building on its original abandoned patent at the same time. The results corroborate a main theoretical contribution of my dissertation.

Fifth, because of differences in the transaction costs of tracking the focal firm's abandoned patents in the *pre*- and *post*-internet era, I divide my sample into two sub-samples based on the year of patent abandonment and conduct the same estimation based on the two sub-samples.[16] The results, which are shown in Table 2.9, reveal that there are observable different effects of patent abandonment on both the amount and the breadth of external forward citations of the abandoned patent. Further, the effects are more statistically significant in the post-internet era, when the costs for external inventors to search the abandoned patent are significantly reduced.

2.5 Conclusion

Innovation is becoming increasingly cumulative and open, which involves the collaboration of multiple inventors to conduct subsequent inventions to commercialize the initial invention. Consequently, to design a patent system that can increase cumulative inventions must consider incentives to provide to the original inventor creating the initial invention, as well as incentives to follow-on inventors developing cumulative inventions that build on the original technologies in the patent. How to facilitate the cumulative invention is a long-standing public policy objective. I submit in this chapter that the focal firm's abandoned patent can reduce the transaction costs of potential follow-on inventors to conduct subsequent research built on the abandoned patent, which can facilitate cumulative inventions. I provide empirical evidence showing that the focal firm's patent

[16] The *USPTO official Gazette* started post-patent abandonment information online in 1995. Therefore, sample 1 (the pre-Internet era sample) includes the patents granted before 1991 (and abandoned in 1995) and sample 2 (the post-Internet era sample) includes patents granted after 1991 (inclusive). In addition, I conduct estimation by each grant-year and the coefficients of *Post*Abandonment* by grant-year are shown in Table 2.10. The results are consistent with the main analysis by separating the samples into two sub-samples.

abandonment will increase both the amount and the breadth of annual external forward citations of the abandoned patents, which is consistent with the "anti-commons" theory addressed in the extant research literature (Galasso & Schankerman, 2011, 2015: Murray & Stern, 2007).

This chapter contributes to debates on whether a patent system enables or constrains innovation. While the literature focuses on the appropriability regime of a patent system (Lerner, 2009), this chapter contributes by analyzing the effectiveness of the patent renewal and patent abandonment system in facilitating cumulative inventions by external inventors (Ayres & Parchomovsky, 2007). This chapter suggests that the patent renewal and patent abandonment system can not only increase invention from the original inventor (Cornelli & Schankerman, 1996), but also can facilitate subsequent cumulative inventions from both the original inventor and the potential external follow-on inventors. Without considering the positive spillovers, the existing literature on patent renewal and abandonment might substantially underestimate the economic value of the focal firm's patent abandonment.

This chapter has several policy and strategic implications for the focal firm, external inventors, and policymakers. First, for the focal firm lacking resources and capabilities to further develop the initial patent internally and thereby incurring high transaction costs in using traditional collaboration mode (such as licensing), it can abandon its patent to facilitate subsequent inventions by attracting potential follow-on inventors with relevant resources and capabilities to develop its patent in a more cost-effective way. Sometimes, the focal firm might choose some hybrid modes of opening up its patent. For example, Procter & Gamble donated their patents for "super aspirin" drug development (Ziegler, Gassman, & Friesike, 2014). The research shows that these hybrid forms of opening up its

intellectual property rights does not have the expected effects on facilitating subsequent innovation. This chapter shows that the focal firm's abandoning its patent can be more effective in facilitating subsequent inventions.

For external inventors, sometimes, instead of creating something that is very new, it would be more efficient to search the abandoned patents first to see whether there are some relevant patented inventions that can be used in their inventions. In recent years, some entrepreneurs and research scholars seek to make it easier for external inventors to search the abandoned patents.[17] According to the literature, the focal firm abandons the patent because this patent is outside the focus of this focal firm or further developing the patent incurs higher costs. Therefore, the abandoned patent can provide opportunities for external inventors with relevant resource and capabilities for further development with low cost. These opportunities are especially important for external inventors lacking bargaining power in negotiating contracts with the focal firm holding the initial patent. Nilsiam and Pearce state: "Instead of reinventing the Wheel, the ability to find IP in the public domain would help accelerate their ability to continue develop more advanced technology" (2016: 2) (In their project, the focal firm's abandoned patent is one type of important IP in the public domain).

For policymakers, to design the patent system based on the intent to facilitate subsequent cumulative inventions, besides considering the strength and scope of patent

[17] For example, Yali Friedman launched DrugPatentWatch.com to collect abandoned patent information of pharmaceutical industry. https://www.drugpatentwatch.com/blog/abandoned-and-expired-patents-in-pharma-manufacturing/ Joshua Pearce, Professor of Michigan Tech, lead the project in refining the search process of the abandoned patents in the hardware industry. https://www.mtu.edu/news/stories/2016/november/inactive-patents-innovate-more-search-less.html

protection, they should also consider the patent renewal system (Hargreaves, 2011). Policymakers can design a system (e.g., increase maintenance fees) to encourage patent-holders to abandon their patents that they cannot further develop internally or through traditional collaboration modes. These policymakers can also refine their search system to reduce costs for external inventors to search for abandoned patents and to facilitate their own inventions. Further, the current chapter shows that in the post-internet era, the external inventors can benefit more from the focal firm's patent abandonment due to the cost reduction of searching knowledge online. Therefore, policymakers could refine the search system for abandoned patent to facilitate cumulative innovation.

As with many empirical studies, there are several limitations of the current chapter, which provide opportunities for future research. First, in this chapter, I cannot fully address the problem of a renewal sample-selection effect. Therefore, I can only show that there might exist an anti-commons effect. However, it is difficult to predict the accurate magnitude of the anti-commons effect of patent.

Second, this chapter employs citation data to represent the cumulative inventions that are built on the initial patent, which is not a perfect measurement. On the one hand, subsequent inventions can be non-patented, which thereby underestimates the cumulative inventions conducted by follow-on inventors. On the other hand, both examiners and applicants (Hegde & Sampat, 2009) can make the citation. Those that are made by examiners cannot be used to reflect knowledge spillovers. Ideally, citations made by examiners should be removed. However, these data are only available after 2001, which is not available for our sample.

Third, this chapter only considers the focal firm relinquishing its IPRs through its patent abandonment. In future research, we can compare this move with other mechanisms (e.g., utilized by Tesla) presented in Table 1.3 and Table 1.4 in chapter 1. We can also make a comparative analysis on whether different strategies have different impacts on cumulative inventions. Furthermore, there can be some interaction between different mechanisms. For example, the focal firm can only abandon its patent in the 4^{th}, 8^{th} and 12^{th} years after the issuance of patent. However, the focal firm can announce to open up its patent at any time. If the focal firm publicly announced to open up its patent before the date for renewal and abandonment, the abandonment of the patent might not create as large a knowledge spillover pool as one might expect based on the empirical results reported in this chapter. My hope is that this chapter will be fruitful for generating future research that is rigorous and relevant to both business policy patenting strategy and to public policy concerning technological invention as well as subsequent innovation.

Tables and Figures

Table 2.1: Summary of "anti-commons" Literature

Paper/Empirical /Industry	"Anti-commons" effect	Main effect	Moderator
Heller and Eisenberg (1998) No Biomedical industry	Yes	A proliferation of intellectual property rights upstream may stifle life-saving innovations further downstream in the course of research and product development.	1. Fragmentation of patent ownership (+): When licenses from too many individual property owners are required, firms may underinvest in the commercialization of downstream technologies due to the high risk of bargaining failure and ex-post holdup. 2. Research tools (+): To use patented research tools, researchers will face increasing difficulties conveying clear title to firms that might develop further discoveries. 3. Early stage technology (+): Licensing transaction costs are likely to arise early in the course of R&D when the outcome of a project is uncertain, the potential gains are speculative, and it is not yet clear that the value of downstream products justifies the trouble of overcoming the "anti-commons". 4. Industry (biomedical+): An "anti-commons" effect in biomedical research may be more likely to endure than in other areas of intellectual property because of the high transaction costs of bargaining, heterogeneous interests among owners, and cognitive biases of researchers.

Table 2.1 (cont.): Summary of "anti-commons" Literature

Walsh, Arora, and Cohen (2003) No Biomedical industry	No	There is a no statistically significant evidence showing that patenting of upstream discoveries would block subsequent downstream innovations.	1. Research tools (NS): None of respondents reported worthwhile projects being stopped because of issues of access to IP rights to research tools. Infringement of research tool patents is difficult to detect and private company usually have high tolerant of infringement to academic research.
Williams (2010) Yes Gene-related patent	Yes	On average, Celera's gene-level IP led to reductions in subsequent scientific research and product development of approximately 20% to 30%.	
Murray and Stern (2007) Yes Gene	Yes	This study finds a modest "anti-commons" effect: the citation rate to the paired publications after the patent grant declines of approximately 10% to 20%.	1. Public sector affiliations (+): The "anti-commons" effect is salient for articles authored by researchers with public sector affiliations because the patent grant is likely to be "news."

Table 2.1 (cont.): Summary of "anti-commons" Literature

Galasso and Schankerman (2015) Yes Cross industry	Yes	The removal of a patent right through courts invalidation leads to about a 50% increase in subsequent citations to the focal patent on average.	1. Fragmentation of patent ownership (+): The effect of patent invalidation is small and statistically insignificant among patents in concentrated technology areas, whereas it is large and statistically significant among patents in fragmented technology fields. 2. Complexity of the technology field (+): The effect of invalidation is more than twice as large in complex technology areas as compared to non-complex technology fields. Patent rights block downstream innovation in computers, electronics, and medical instruments, but not in drugs, chemicals, or mechanical technologies. 3. Firm size (+): The effect of patent rights on later innovation is entirely driven by the invalidation of patents owned by large firms, which increases the number of small innovators subsequently citing the focal patent. There is no statistically significant effect of patent rights on later citations when small- or medium-sized firms own the invalidated patents.

Table 2.1 (cont.): Summary of "anti-commons" Literature

Huang and Murray (2009) Yes Human gene	Yes	The grant of gene patent negatively impacts the rate of follow-on publications, as shown by the 17% decline in the expected rate of forward citations to the patent's paired paper.	1. Patent scope (+): There is a statistically significant, though quite modest, impact of broader scope gene patents on subsequent citations to a gene paper (both relative to the mean and in absolute terms), with an incremental decline of about 1% on subsequent citations for each unit increase in number of patent class. 2. Public sector (-): For production of public knowledge in human gene, the main impact of patenting arises through private sector gene patents. 3. Fragmentation of patent ownership (+): For any given patent, an increase in ownership from one to two organizations for a claimed gene would result in an incremental 3.5% decline in the forward citations of the paired paper. 4. Patent strength (+/NS): There is a statistically insignificant effect on subsequent citations of a publication as the patent increased in number of claims (both relative to the mean and in absolute terms). 5. Usefulness of patented knowledge (+): The negative impact of patent grant is centered on genes and on genetic knowledge that are centered for human diseases. 6. Patent thicket (+): Patent grant over genes associated with one patent significantly depresses the citations by more than 7%, but genes patented 5 to 7 times show a significant post-grant decline of more than 9%. The denser the thicket of patents over knowledge claimed in a publication, the more the patent thicket negatively impacts the rate of follow-on publications.

Table 2.1 (cont.): Summary of "anti-commons" Literature

Wen, Ceccagnoli, and Forman (2015) Yes Software industry	Yes	A 10% increase in the Commons' patent claims in a software market is associated with an average 1% to 3% increase in the rate of OSS entry by startups into that market.	1. Fragmentation of market (-): As the market concentration increases from the 10^{th} to 90^{th} percentile, the marginal effect of a 10% increase in The Commons increases from 0%-1.7% to 1.5%-2.7%. 2. Cumulativeness of market (+): As market cumulativeness increases from the 10^{th} to 90^{th} percentile, the marginal effect of a 10% increase in The Commons' patent claims on OSS entry increases from 0.6%-1.3% to 4.0%-5.5%.
Sampat and Williams (2015) Yes Human gene	No	On average, gene patents have not had quantitatively important effects on follow-on innovation.	
Hall and Helmers (2013) Yes Environmental related industry	No	Pledging patents by making them available to third parties royalty-free has no discernible impact on the diffusion of green technology. The removal of existing patents might have little effect on the spreading of the previously protected technologies.	

Table 2.1 (cont.): Summary of "anti-commons" Literature

Murray, Aghion, Dewatripont, Kolev, and Stern (2010) Yes Research tools	Yes	The NIH agreements (openness of two research tools) result in a significant increase in the level of follow-on research. The bulk of new citations arise from articles published by "new" researchers or institutions.	
Mowery, Thompson, and Ziedonis (2014) Yes	Yes	In general, licenses are associated with an increase in journal citations to related scientific publications. The related scientific publications experience a significant decline in citations following the execution of the license when the underlying discovery is a research input (which are identified through the use of material transfer agreements)	

Table 2.2: Summary of empirical papers on patents and cumulative innovation

Paper/Research Question/Data/Methodology	**Model specification**	**Results**
Williams (2010) How did Celera's gene-level IP influence subsequent scientific research and product development? Scientific research is drawn from Online Mendelian Inheritance in Man (OMIM) database. Product development is drawn from GeneTEsts.org. OLS (heteroskedasticity-robust standard error clustered at the gene level)	1. Cross-section estimates $(outcome)_g = \alpha + \beta(Celera)_g + \lambda'(covariates)_g + \varepsilon_g$ "*Celera*": 0/1, =1 for Celera gene. "*Indicator variables for year of disclosure*": 0/1 indicator variables for the year sequence for the gene was disclosed. "*Number of publications in each year 1970-2000*": count variables for the number of publications on each gene in each year from 1970 to 2000. "*Detailed cytogenetic & Molecular covariates*": 0/1 indicator variables for the chromosome (1-22, X, or Y) and arm (p or q) on which a gene is located; continuous variables for regions, band, sub-band, start base pair, and end-base pair; and 0/1 indicator variables for the orientation of the gene on the genome assembly (plus or minus). 2. Panel estimates $(outcome)_{gy} = \alpha + \delta_g + \gamma_y + \beta(Celera)_{gy} + \varepsilon_{gy}$ "*Celera*": an indicator for whether gene g had been sequenced only by Celera as of that year.	1. Across a range of empirical specification, the study finds evidence that Celera's IP led to reductions in subsequent scientific research and product development approximately 20% to 30%. 2. A caveat of this interpretation is that the results could reflect the substitution of innovative effort away from Celera genes towards non-Celera genes (as opposed to a net decrease in total innovation over the set of all genes).

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Murray and Stern (2007) The paper use patent-paper pairs to evaluate the salience of IPR on cumulative innovation. 1. To what extent does public scientific knowledge disclosed at a patent-paper pair differs in its future cumulative impact on public domain research (as measured by forward citations to the publications) from papers that are in similar in topic, published in the same journal in the same time-period, but never receive IPR? 2. How does the grant of formal patent rights over such knowledge influence the trajectory of forward citations and therefore the impact of the scientific research findings in the public domain? 340 peer-reviewed scientific articles appearing between 1997 and 1999 in *Nature Biotechnology*. Difference-in-differences	1. Baseline empirical test $CITES_{i,t} = f(\varepsilon_{i,t};\ \gamma_i + \delta_{t-pubyear} + \beta_t + \psi_{WINDOW} WINDOW_{i,t} + \psi_{POST-GRANT} POST-GRANT_{i,t})$ γ_i is fixed effect for each article, $\delta_{t-pubyear}$ captures the age of the article, β_t is a fixed effect for each citation year, WINDOW is a dummy variable equal to one in the year in which a patent is granted and POST-GRANT is a dummy variable equal to one only for years after the patent grant year for an individual article. $CITES_{i,t}$: number of citations to article *i* in year *t*.	1. The study finds a modest anti-commons effect (the citation rate after the patent grant declines by approximately 10% to 20%) 2. The decline becomes more pronounced with the number of years elapsed since the date of the patent grant and is particularly salient for articles authored by researchers with public sector affiliations.

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Smeets (2014) The study evaluates the impact of patent litigation on the subsequent corporate R&D intensity of alleged infringers. 534 public US firms that were sued for patent infringement in the US during the period 2000-2012 Propensity Score Matching techniques with differences-in-differences estimation	1. Propensity score matching $$P(L_{it} = 1 \mid X_{it}) = \phi\left(X_{it}^{k}\beta_{k}\right) + \varepsilon_{it}$$ where *i* and *t* index firm and year respectively, *L* is a dummy indicating whether the fir was involved in a patent lawsuit (1) or not (0), *X* is a vector of explanatory variables (R&D intensity; firm size; capital intensive; states; industry; year dummies; patent stock), $\phi(.)$ denotes the cumulative normal distribution function, and $\mathcal{E}$ is an IID error term. 2. Difference-in-differences estimation $$RDI_{it} = \gamma_0 + \gamma_1 L_i + \gamma_2 P_\tau + \gamma_3 L_i \times P_\tau + \varepsilon_{it})$$ *RDI* is R&D intensity, *L* is the involvement in patent litigation (1) or not (0), P is a dummy variable that takes the value 0 in the year of litigation (which is normalized to 0) and the value 1 in τ years after the year of litigation, and ε is an IID error term.	Corporate R&D intensity is reduced, generally during the first three years following patent litigation, but only in small firms (with less than 500 employees) that are involved in costly lawsuits (as proxied by the number of legal documents field). The impact is substantial: the reduction in R&D intensity is between 2.6-4.7% points.

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Mezzanotti (2016) How will patent litigation influence innovation? The paper develop a new research design that exploits a landmark legal decision, the 2006 Supreme Court decision "ebay vs. MercExchange." N/A Difference-in-differences	Difference-in-differences $y_{it} = \alpha_j + \alpha_t + \beta(Exposure_j \times Post) + \gamma X_{jt} + \epsilon_{jt}$ y_{it} is an outcome (number of patent) of firm j at time t, $Post = 1\{time > decision\}$, (α_j, α_t) are a set of firm and time fixed effects and $Exposure_j$ is the index of exposure to litigation, as previously discussed. X_{jt} is a series of control variables of firm-level characteristics measured at the time of decision.	1. Firms that were more exposed to litigation before the decision increased patenting more after the decision. These effects are both economically relevant and statistically significant. 2. The decision also positively affected the quality of innovation. After the decision, firms are more likely to develop a potential "breakthrough innovation," defined as a patent that is at the top of the citation distribution within the same patent class and year group. The results suggest that better enforcement made firms more prone to take riskier projects. 3. After the decisions, firms reshuffled their internal resources towards projects in higher litigation areas. Firms entering in new technology fields, where litigation risks are high, drive this effect. 4. Firms are likely to be financial constrained before the decision increased R&D intensity more in its aftermath.

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Galasso and Schankerman (2015) How will patent rights affect the process of cumulative innovation? The study adopts a novel identification strategy to estimate the causal effect of patent protection on cumulative innovation. The study use the patent invalidity decisions of the U.S. Court of Appeal for the Federal Circuit, which was established in 1982 and has exclusive jurisdiction in appellate cases involving patents. The decisions of the Court of Appeal for the Federal Circuit, and the U.S. Patent and Trademark Office (USPTO) patent dataset. IV estimation (the study exploits the random allocation of judges, together with variation in their propensity to invalidate patents, to construct an instrumental variable that addresses the potential endogeneity of invalidity decision.	1. Baseline specification $\log(PostCites_p + 1) = \beta Invalidated_p + \lambda_1 \log(PreCites + 1) + \lambda_2 \log(PreSelfCites_p + 1) + \lambda_3 \log(Claims_p) + Age_p + Year_p + Tech_p + \varepsilon_p$ 2. Two stage model $Invalidated_p = \alpha \widehat{P_p} + \theta X_p + u_p$ $\log(PostCites_p + 1) = \beta \widehat{Invalidated_p} + \gamma X_p + \varepsilon_p$	1. Patent invalidation leads to about a 50% increase in subsequent citations to the focal patent on average, and this finding is robust to a wide variety of alternative specifications and controls. 2. The impact of patent invalidation on subsequent innovation is highly heterogeneous. The positive impact of invalidation on citation is concentrated on a small subset of patents that have unobservable characteristics associated with a lower probability of invalidity (i.e. stronger patents). There is also large variation across broad technology fields in the impact of patent invalidation, and the effect is concentrated in fields that are characterized by two features: complex technology and high fragmentation of patent ownership. 3. The effect of patent rights on later innovation depends critically on the characteristics of the transacting parties. The impact is entirely driven by the invalidation of patents owned by large firms, which increases the number of small innovators subsequently citing the focal patent. There is no statistically significant effect of patent rights on later citations when small- or medium-sized firms own the invalidated patents.

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Huang and Murray (2009) How do firm's patent strategies, and the landscape of private property rights they collectively produce, influence the long-run production of public knowledge? 4,270 U.S. patents claiming uses of human genes as identified by stringent bioinformatics criteria. Negative binomial regression model	1. $Annual\ citations_{i,t} = f(\epsilon_{i,t};\ \alpha patent\ window_{i,t} + \beta patent\ in\ force_{i,t} + \varphi number\ of\ authors_i + \zeta number\ of\ address_i + \delta U.S.address_i + \eta public\ address_i + \mu impact\ factor_i + \chi paper\ age\ fixed\ effects_{t-paper\ year} + \psi citation\ year\ fixed\ effects_t)$ 2. $Annual\ citations_{i,t} = f(\epsilon_{i,t};\ \alpha patent\ window_{i,t} + \beta patent\ in\ force_{i,t} + \lambda paper\ fixed\ effects_i + \chi paper\ age\ fixed\ effects_{t-paper\ year} + \psi citation\ year\ fixed\ effects_t)$ 3. $Annual\ citations_{i,t} = f$	1. The grant of a gene patent negatively impacts the rate of follow-on publications, as shown by the17% decline in the expected rate of forward citations to the patent's paired paper. 2. There is a statistically significant, although quite modest, impact of broader (scope) gene patents on subsequent citations to a gene paper (both relative to the mean and in absolute terms), with an incremental decline of about 1 percent on subsequent citations for every unit increase in number of patent class. 3. For the production of public knowledge (in human genetics), the main impact of patenting arises through private sector gene patents. 4. For any given patent, an increase in ownership from one to two organizations for a claimed gene would result in an incremental 3.5% decline in the forward citations of the paired paper. 5. The negative impact of patent grant is centered on genes and on genetic knowledge that are critical for human diseases.

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Sakakibara and Branstetter (2001) Does an expansion of patent scope induce additional innovative effort? How responsive are firms to changes in patent design? 307 publicly traded Japanese manufacturing firms drawn from various industries	$r_{it} = \beta_0 + \beta_1 q_{it} + \beta_2 s_{it} + \sum_c \delta_c D_c + \gamma_t + \theta_i + \varepsilon_{it}$ Here r_{it} is the natural log of real R&D spending by firm i in year t and q_{it} is a measure of firm-level "average Q". D is 14 industry dummy variables to control for differences in levels of R&D spending across industries. θ_i is firm-level research productivity, which is not observed.	The study finds no evidence of a statistically and economically significant increase in either R&D spending or innovative output that could plausibly be attributed to these reforms. The empirical evidence suggests that the responsiveness to changes in patent scope is limited.
Wen, Ceccagnoli, and Stern (2016) The study examines whether a firm's intellectual property strategy in support of the open source software (OSS) community stimulates new OSS product entry by start-up software firms. 2,054 start-up software firms from the 2004 and 2010 editions of the CorpTech Directory of Technology Companies that primarily operate in the U.S. prepackaged software industry.	1. Baseline regression $E(Y_{jt}\|X_{jt}, \alpha_j) = \lambda_{jt} = \alpha_j \exp(X'_{jt}\beta)$ $X'_{jt}\beta = \beta_1 The\ Commons_{jt} + \gamma_1 Patent\ Thicket_{jt-1} + \gamma_2 Sales\ Growth_{jt} + \gamma_3 Market\ Patents_{jt-1} + \tau_t$ 2. $X'_{jt}\beta = \beta_1 The\ Commons_{jt} + \beta_2 The\ Commons_{jt} * Cumulativeness_{jt-1} + \gamma_1 Patent\ Thicket_{jt-1} + \gamma_2 Sales\ Growth_{jt} + \gamma_3 Market\ Patents_{jt-1} + \tau_t$ 3. $X'_{jt}\beta = \beta_1 The\ Commons_{jt} + \beta_2 The\ Commons_{jt} * fragmentation_{jt-1} + \gamma_1 Patent\ Thicket_{jt-1} + \gamma_2 Sales\ Growth_{jt} + \gamma_3 Market\ Patents_{jt-1} + \tau_t$	1. A 10% increase in the Commons' patent claims in a software market is associated with an average 1% to 3% increase in the rate of OSS entry by startups into that market. 2. Introduction of The Commons influences entry, especially in those markets where innovations are highly cumulative and where patent ownership is concentrated. - As market cumulativeness increases from the 10th to 90th percentile, the marginal effect of a 10% increase in The Commons' patent claims on OSS entry increases from 0.6%-1.3% to 4.0%-5.5%. - As the market concentration increases from the 10th to 90th percentile, the marginal effect of a 10% increase in The Commons increases from 0%-1.7% to 1.5%-2.7%

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Cockburn and MacGarvie (2011) To what extent are firms kept out of a market by patents covering related technologies? 27 narrowly defined categories of software products during the period 1990-20044 Difference-in-difference	$y_{it}^{*} = \beta' x_{it} + \varepsilon_{it} \quad y_{it} = 1 \; if \; y_{it}^{*} > 0, 0 \; otherwise$ where x_{it} is a vector of variables capturing costs and benefits of entry and the dependent variable y_{it} equals 1 in the year that the firm enters a market, and 0 otherwise.	1. Controlling for demand, market structure, average patent quality, and other factors, the study finds a 10% increase in the number of patents relevant to market reduces the rate of entry by 3%-8%. 2. This relationship intensified following expansions in the patentability of software in the mid-1990s. 3. Potential entrants with patent applications relevant to a market are more likely to enter it.
Murray, Aghion, Dewatripont, Kolev, and Stern (2010) How does openness influence the rate and direction of follow-on research? Difference-in-differences	$Annual\ Citations_{jt} = f(\varepsilon_{jt}; \gamma_j + \beta_t + \delta_{t-PubYear} + \psi_0 NIHMoUWindow_{jt} + \psi_1 PostNIHMoU_{jt})$ γ_j is an article fixed effect (conditioned out in estimation), β_t are citation-year effects and $\delta_{t-PubYear}$ are article fixed effects. $New\ Authors_{jt} = f(\varepsilon_{jt}; \gamma_j + \alpha t + \beta_t + \delta_{t-PubYear}^{NEW} + \psi_0^{NEW} NIHMoUWindow_{jt} + \psi_1^{NEW} PostNIHMoU_{jt})$ $Old\ Authors_{jt} = f(\varepsilon_{jt}; \gamma_j + \alpha t + \beta_t + \delta_{t-PubYear}^{OLD} + \psi_0^{OLD} NIHMoUWindow_{jt} + \psi_1^{OLD} PostNIHMoU_{jt})$ γ_j is a mouse-article fixed effect, α parameterizes a linear calendar-time-trend difference between the two equations, β_t is a calendar-time fixed effect, and $\delta_{t-PubYear}^{NEW}$ and $\delta_{t-PubYear}^{OLD}$ are article-age fixed effect.	1. The NIH agreements result in a significant increase in the level of follow-on research. More importantly, the bulk of new citations arise from articles published by "new" researchers or institutions. 2. The results offer direct evidence that increased scientific openness is associated with the establishment of entirely new research lines. Specially, the openness agreements lead to a significant increase in the diversity of the journals in which mouse-articles in the treatment group are cited, and, perhaps more strikingly, a significant increase in the number of previously unused "keywords" describing the research contributions of the citing articles 3. Increased openness is not associated with a reduction in the number of new mouse-articles; instead, the number of new mice created either increase or remains the same after the openness shocks.

Table 2.2 (cont.): Summary of empirical papers on patents and cumulative innovation

Sampat and Williams (2015) Do patents on one specific technology – human genes – have affected follow-on scientific research and product development? USPTO patent applications that claim human genes Two quasi-experiment 1. Comparison of follow-on innovation on genes included in accepted and rejected patent applications. 2. Instrument variable: "leniency" of the assigned patent examiner.	1. Regression analysis: comparison of accepted and rejected patent applications. DV: Follow-on Scientific research: scientific publication related to each gene. Product commercialization: gene-related pharmaceutical test; gene-based diagnostic tests. Treatment vs. control: The estimation compare differences in follow-on innovation on genes claimed in at least one granted patent relative to genes claimed in at least one patent application but never in a granted patent. 2. IV estimation First stage $1(patent\ grant)_{it\ ja} = \alpha + \beta * Z_{it\ ja} + \sum_{at} 1(art\ unit)_{ta} + \varepsilon_{it\ ja}$ where the outcome variable $1(patent\ grant)_{it\ ja}$ is an indicator variable equal to one if patent application i was granted a patent, $Z_{it\ ja}$ is leave-one-out-mean gene patent rate instrument , and $\sum_{at} 1(art\ unit)_{ta}$ are a set of Art Unit-by-application year fixed effect. $$Z_{it\ ja} = \frac{n_{grant_j} - 1(grant_i = 1)}{n_{application} - 1}$$ where n_{grant_j} is the number of patents granted by examiner j, $n_{aplication_j}$ is the number of patent applications reviewed by examiner j, and $grant_i$ is an indicator equal to 1 if patent application i was granted a patent.	1. On average, gene patents have not had quantitatively important effects on follow-on innovation.

Table 2.3 (1): Summary statistics (renewed patents, abandoned patents, and all Patents)

		Before Match					After Match				
		N	Mean	S.D.	Min	Max	N	Mean	S.D.	Min	Max
Prior External Forward Citations	Renewed patents	2335702	4.961	7.456	0	376	2254758	4.346	5.282	0	123
	Abandoned patents	325682	3.127	4.659	0	224	324352	3.075	4.293	0	121
	Difference		1.834***					1.271***			
Backward Citations	Renewed patents	2335702	7.721	10.32	1	678	2254758	6.990	7.128	1	318
	Abandoned patents	325682	6.517	12.08	1	383	324352	6.367	7.162	1	318
	Difference		1.204***					0.623			
Strength	Renewed patents	2335702	14.769	0.008	1	868	2254758	14.074	10.283	1	213
	Abandoned patents	325682	13.130	0.018	1	232	324352	13.016	9.739	1	192
	Difference		1.639***					1.058***			
Scope	Renewed patents	2335702	1.497	0.857	1	24	2254758	1.495	0.854	1	24
	Abandoned patents	325682	1.496	0.853	1	16	324352	1.495	0.852	1	16
	Difference		0.001***					-0.000			
# Assignees	Renewed patents	2335702	1.026	0.177	1	10	2254758	1.026	0.177	1	10
	Abandoned patents	325682	1.020	0.166	1	10	324352	1.020	0.166	1	10
	Difference		0.006***					0.006			
Originality	Renewed patents	2335702	0.513	0.349	0	1	2254758	0.512	0.351	0	1
	Abandoned patents	325682	0.531	0.356	0	1	324352	0.531	0.357	0	1
	Difference		-0.018***					-0.019***			
Generality	Renewed patents	2335702	0.549	0.327	0	1	2254758	0.549	0.329	0	1
	Abandoned patents	325682	0.573	0.343	0	1	324352	0.572	0.343	0	1
	Difference		-0.024***					-0.023***			

Table 2.3 (1, cont.): Summary statistics (renewed patents, abandoned patents, and all Patents)

Diversification	Renewed patents	2335702	0.689	0.261	0	0.950	2254758	0.690	0.260	0	0.950
	Abandoned patents	325682	0.607	0.314	0	0.950	324352	0.607	0.314	0	0.950
	Difference		0.082***					0.083***		0	0.950
Technology focus	Renewed patents	2335702	0.315	0.301	0	1	2254758	0.313	0.300	0	1
	Abandoned patents	325682	0.386	0.348	0	1	324352	0.386	0.348	0	1
	Difference		-0.071***					-0.073***			1
Firm size	Renewed patents	2335702	0.125	0.331	0	1	2254758	0.125	0.331	0	1
	Abandoned patents	325682	0.247	0.429	0	1	324352	0.247	0.431	0	1
	Difference		-0.121***					-0.121***			

Table 2.3 (2): Mean of external forward citations for matched samples (before and after decisions)

		Before Match			After Match		
		# of Obs.	Pre	Post	# of Obs.	Pre	Post
# of External Forward Citations	Abandon	162841	0.732 (1.508)	0.565 (1.305)	162176	0.732 (1.502)	0.565 (1.300)
	Renew	1167851	1.064 (2.147)	0.794 (1.887)	1127379	1.051 (2.080)	0.780 (1.801)
	Difference		-0.331*** (0.005)	-0.229*** (0.005)		-0.319*** (0.005)	-0.216*** (0.005)
# of Patent Class	Abandon	162841	0.558 (0.905)	0.430 (0.806)	162176	0.558 (0.905)	0.430 (0.806)
	Renew	1167851	0.837 (1.315)	0.613 (1.147)	1127379	0.831 (1.291)	0.607 (1.119)
	Difference		-0.279*** (0.003)	0.183*** (0.003)		-0.273*** (0.003)	-0.177*** (0.003)

Table 2.4: Results of Difference-in-Differences

	(1) Log(EFC+1)	(2) CEM: Log(EFC+1)	(3) Log(Breadth+1)	(4) CEM: Log(Breadth+1)
Post	-0.133	-0.110	-0.032	-0.029
	(0.001)***	(0.002)***	(0.000)***	(0.000)***
Abandon	-0.077	-0.063	-0.031	-0.029
	(0.002)***	(0.005)***	(0.001)***	(0.000)***
Post * Abandon	**0.038**	**0.015**	**0.016**	**0.013**
	(0.002)* **	**(0.007)*** **	**(0.001)*** **	**(0.002)*** **
External Forward Citations			0.727	0.725
			(0.000)	(0.000)***
Prior Forward Citations	2.471	2.525	0.008	0.018
	(0.018)***	(0.005)***	(0.001)***	(0.001)***
Backward Citations	0.009	0.009	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Strength	0.008	0.007	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Scope	0.018	0.016	0.001	0.001
	(0.002)***	(0.001)***	(0.000)***	(0.000)***
No. Assignee	-0.009	-0.008	-0.008	-0.008
	(0.007)	(0.007)	(0.001)***	(0.000)***
Originality	0.072	0.062	-0.004	-0.004
	(0.004)***	(0.004)***	(0.000)***	(0.001)***
Generality	0.049	0.039	-0.005	0.004
	(0.003)***	(0.004)***	(0.000)***	(0.001)***
Diversification	-0.302	-0.261	0.079	0.077
	(0.011)***	(0.010)***	(0.001)***	(0.001)***
Technology Focus	-0.109	-0.119	0.030	0.029
	(0.009)***	(0.008)***	(0.001)***	(0.001)***
Size	-0.039	-0.035	-0.021	-0.020
	(0.004)***	(0.004)***	(0.000)***	(0.001)***
Constant	1.674	0.638	0.200	-0.012
	(0.760)**	(0.815)	(0.042)***	(0.111)
Tech Dummies	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes
R^2	0.23	0.16	0.786	0.778
N	2,171,226	2,132,605	2,171,226	2,132,605

Note:

1. * $p<0.1$; ** $p<0.05$; *** $p<0.01$
2. Robustness Standard Errors are in parentheses

Table 2.5: Additional Analysis (1) Results for 2nd and 3rd patent renewal and abandonment

	(1) 2nd renew Log(EFC+1)	(2) 3rd renew: Log(EFC+1)	(3) 2nd renew Log(Breadth+1)	(4) 3rd renew: Log(Breadth+1)
Post	-0.121	-0.125	-0.081	-0.066
	(0.001)***	(0.001)***	(0.001)***	(0.001)***
Abandon	-0.073	-0.056	-0.041	-0.021
	(0.001)***	(0.005)***	(0.001)***	(0.001)***
Post * Abandon	**0.046**	**0.040**	**0.021**	**0.010**
	(0.002)* **	**(0.002)*** **	**(0.001)*** **	**(0.001)*** **
External Forward Citations			0.727	0.725
			(0.000)***	(0.000)***
Prior Forward Citations	0.038	0.036	0.013	0.010
	(0.000)***	(0.000)***	(0.001)***	(0.001)***
Backward Citations	0.001	0.001	-0.000	-0.000
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Strength	0.002	0.002	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Scope	0.004	0.004	0.005	0.003
	(0.000)***	(0.001)***	(0.000)***	(0.000)***
No. Assignee	-0.006	-0.008	-0.005	-0.007
	(0.002)***	(0.002)***	(0.001)***	(0.001)***
Originality	0.015	0.014	0.009	0.008
	(0.001)***	(0.001)***	(0.000)***	(0.001)***
Generality	0.031	0.038	0.019	0.023
	(0.001)***	(0.001)***	(0.001)***	(0.001)***
Diversification	-0.039	-0.048	0.007	-0.006
	(0.003)***	(0.010)***	(0.002)***	(0.002)***
Technology Focus	-0.013	-0.017	-0.011	-0.010
	(0.003)***	(0.003)***	(0.002)***	(0.002)***
Size	0.014	0.015	0.010	0.009
	(0.001)***	(0.001)***	(0.000)***	(0.001)***
Constant	-0.146	-0.043	-0.099	-0.035
	(0.043)***	(0.045)	(0.029)***	(0.024)***
Tech Dummies	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes
R^2	0.42	0.41	0.79	0.78
N	1,929,912	1,203,861	1,929,912	1,203,861

Note:

1. * $p<0.1$; ** $p<0.05$; *** $p<0.01$
2. Robustness Standard Errors are in parentheses

Table 2.6: Additional Analysis (2)

	DV: # of External Citation		DV: # of Patent Classes	
Abandon	-0.071	(0.002)***	-0.034	(0.001)***
Year1	0.103	(0.002)***	-0.005	(0.000)***
Year1 * Abandon	**-0.013**	**(0.002)*** **	**-0.003**	**(0.001)*** **
Year2	0.116	(0.001)***	-0.015	(0.000)***
Year2 * Abandon	**-0.013**	**(0.002)*** **	**-0.000**	**(0.001)**
Year3	0.075	(0.001)***	-0.027	(0.000)***
Year3 * Abandon	**-0.003**	**(0.002)**	**-0.048**	**(0.006)*** **
Year4	0.011	(0.001)***	-0.043	(0.000)***
Year4 * Abandon	**0.015**	**(0.002)*** **	**0.012**	**(0.001)*** **
Year5	-0.058	(0.001)***	-0.060	(0.000)***
Year5 * Abandon	**0.035**	**(0.002)*** **	**0.021**	**(0.000)*** **
Year6	-0.099	(0.001)***	-0.069	(0.000)***
Year6 * Abandon	**0.047**	**(0.002)*** **	**0.024**	**(0.001)*** **
Year7	-0.132	(0.001)***	-0.077	(0.000)***
Year7 * Abandon	**0.057**	**(0.002)******	**0.028**	**(0.001)******
Year8	-0.156	(0.001)***	-0.083	(0.003)***
Year8 * Abandon	**0.064**	**(0.002)*** **	**0.031**	**(0.001)*** **
Backward Citations	0.003	(0.000)***	0.001	(0.000)***
No. Claims	0.003	(0.000)***	0.001	(0.000)***
Scope	0.007	(0.000)***	0.001	(0.001)***
No. Assignees	0.002	(0.001)***	-0.008	(0.000)******
Originality	0.019	(0.001)***	-0.004	(0.000)***
Generality	0.020	(0.001)***	-0.007	(0.000)***
Diversification	-0.093	(0.001)***	-0.299	(0.005)***
Tech. Focus	-0.036	(0.001)***	0.083	(0.000)***
Size	-0.003	(0.001)***	-0.021	(0.000)***
Constant	0.506	(0.101)***	0.114	(0.051)**
Tech Dummies	Yes		Yes	
Year Dummies	Yes		Yes	
R^2	0.15		0.78	
N	9, 250,046		9, 250,046	

Note:

1. * $p<0.1$; ** $p<0.05$; *** $p<0.01$
2. Robustness Standard Errors are in parentheses

Table 2.7 (1): Additional analysis (3): Number of External Forward Citations

	(5) DV: CEM log(EFC_2year +1)	(6) DV: CEM log(EFC_3year +1)	(7) DV: CEM log(EFC_4year +1)
Post	-0.205	-0.212	-0.137
	(0.001)***	(0.001)***	(0.001)***
Abandon	-0.088	-0.097	-0.100
	(0.002)***	(0.002)***	(0.002)**
Post*Abandon	**0.017**	**0.011**	**0.002**
	(0.003)* **	**(0.003)** **	**(0.001)** **
Prior Forward Citations	0.795	0.855	0.883
	(0.002)***	(0.002)***	(0.002)***
Backward Citations	0.004	0.006	0.006
	(0.000)***	(0.000)***	(0.000)***
Strength	0.004	0.005	0.005
	(0.000)***	(0.000)***	(0.000)***
# Assignee	-0.001	0.003	0.007
	(0.003)	(0.003)	(0.003)***
Scope	0.010	0.012	0.014
	(0.001)***	(0.003)***	(0.001)***
Originality	0.028	0.032	0.033
	(0.001)***	(0.002)***	(0.002)***
Generality	0.034	0.044	0.049
	(0.002)***	(0.002)***	(0.002)***
Diversification	-0.133	-0.159	-0.171
	(0.004)***	(0.004)***	(0.004)***
Technology Focus	-0.067	-0.076	-0.081
	(0.003)**	(0.004)***	(0.004)***
Small Entity	0.005	0.004	0.002
	(0.001)***	(0.002)***	(0.002)***
Constant	1.175	1.665	2.172
	(58.45)**	(59.05)**	(58.30)**
Tech Dummies	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes
R^2	0.15	0.16	0.17
N	2,105,249	1,819,486	1,533,811

Table 2.7 (2): Additional analysis (3): Number of Patent Classes

	(8) DV: CEM log(Breadth_2year +1)	(9) DV: CEM log(Breadth_3year +1)	(10) DV: CEM log(Breadth_4year +1)
Post	-0.055	-0.075	-0.093
	(0.000)**	(0.000)***	(0.000)***
Abandon	-0.046	-0.057	-0.063
	(0.001)***	(0.001)***	(0.001)***
Post*Abandon	**0.020**	**0.026**	**0.029**
	(0.001)* **	**(0.001)** **	**(0.001)*** **
EFC	0.735	0.733	0.064
	(0.000)***	(0.000)***	(0.001)***
Prior Forward Citations	0.031	0.046	0.064
	(0.001)***	(0.001)***	(0.001)***
Backward Citations	0.001	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***
Strength	0.001	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***
# Assignee	-0.012	-0.015	-0.015
	(0.001)**	(0.001)***	(0.001)***
Scope	0.002	0.002	0.003
	(0.000)***	(0.000)***	(0.000)***
Originality	-0.006	-0.008	-0.009
	(0.001)***	(0.001)***	(0.001)***
Generality	-0.007	-0.010	-0.013
	(0.001)***	(0.001)***	(0.001)***
Diversification	0.121	0.151	-0.173
	(0.002)***	(0.002)***	(0.002)***
Technology Focus	0.047	0.059	0.071
	(0.001)***	(0.001)***	(0.002)***
Size	-0.031	-0.039	-0.044
	(0.001)***	(0.000)***	(0.001)***
Constant	1.175	1.665	2.172
	(58.45)	(59.05)	(58.30)**
Tech Dummies	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes
R^2	0.802	0.809	0.810
N	2,105,249	1,819,486	1,533,811

Note:

1. * $p<0.1$; ** $p<0.05$; *** $p<0.01$

2. Robustness Standard Errors are in parentheses

Table 2.8: Additional analysis (4) Results include the self-citations in DV

	(1) Log(FC+1)	(2) CEM: Log(FC+1)	(3) Log(Breadth+1)	(4) CEM: Log(Breadth+1)
Post	-0.158	-0.134	-0.033	-0.029
	(0.001)***	(0.001)***	(0.000)***	(0.000)***
Abandon	-0.111	-0.097	-0.031	-0.029
	(0.002)***	(0.002)***	(0.001)***	(0.000)***
Post * Abandon	**0.053**	**0.029**	**0.016**	**0.013**
	(0.002)* **	**(0.007)*** **	**(0.001)*** **	**(0.002)*** **
External Forward Citations			0.727	0.725
			(0.000)	(0.000)***
Prior Forward Citations	2.471	2.525	0.008	0.018
	(0.018)***	(0.005)***	(0.001)***	(0.001)***
Backward Citations	0.009	0.009	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Strength	0.008	0.007	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Scope	0.018	0.016	0.001	0.001
	(0.002)***	(0.001)***	(0.000)***	(0.000)***
No. Assignee	-0.009	-0.008	-0.008	-0.008
	(0.007)	(0.007)	(0.001)***	(0.000)***
Originality	0.072	0.062	-0.004	-0.004
	(0.004)***	(0.004)***	(0.000)***	(0.001)***
Generality	0.049	0.039	-0.005	0.004
	(0.003)***	(0.004)***	(0.000)***	(0.001)***
Diversification	-0.302	-0.261	0.079	0.077
	(0.011)***	(0.010)***	(0.001)***	(0.001)***
Technology Focus	-0.109	-0.119	0.030	0.029
	(0.009)***	(0.008)***	(0.001)***	(0.001)***
Size	-0.039	-0.035	-0.021	-0.020
	(0.004)***	(0.004)***	(0.000)***	(0.001)***
Constant	1.674	0.638	0.200	-0.012
	(0.760)**	(0.815)	(0.042)***	(0.111)
Tech Dummies	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes
R^2	0.191	0.156	0.786	0.778
N	2,171,226	2,132,605	2,171,226	2,132,605

Note:

1. * p<0.1; ** p<0.05; *** p<0.01
2. Robustness Standard Errors are in parentheses

Table 2.9: Robustness check (6) Results by Samples at *Pre-* and *Post-* Internet era

	Log (EFC+1) Pre-Internet	Log (EFC+1) Post-Internet	Log (Breadth+1) Pre-Internet	Log (Breadth+1) Post-Internet
Post	-0.004	-0.180	-0.015	-0.042
	(0.001)***	(0.001)***	(0.001)***	(0.000)***
Abandon	-0.058	-0.081	-0.028	-0.032
	(0.002)***	(0.002)***	(0.001)***	(0.001)***
Post * Abandon	**0.001**	**0.045**	**0.009**	**0.020**
	(0.003)	**(0.003)*** **	**(0.001)*** **	**(0.001)*** **
External Forward Citations			0.761	0.715
			(0.001)***	(0.001)***
Prior Forward Citations	0.531	0.486	0.012	0.008
	(0.006)***	(0.004)***	(0.002)***	(0.001)***
Backward Citations	0.007	0.003	0.002	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Strength	0.002	0.003	0.001	0.001
	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Scope	0.011	0.005	0.001	0.001
	(0.001)***	(0.001)***	(0.000)***	(0.000)***
No. Assignee	0.005	-0.006**	-0.013	-0.007
	(0.004)	(0.002)	(0.002)***	(0.001)***
Originality	0.017	0.025	-0.005	-0.003
	(0.002)***	(0.001)***	(0.001)***	(0.001)***
Generality	0.008	0.030	-0.009	-0.003
	(0.002)***	(0.001)***	(0.001)***	(0.001)***
Diversification	-0.063	-0.109	0.094	0.074
	(0.005)***	(0.004)***	(0.002)***	(0.002)***
Technology Focus	-0.032	-0.046	0.041	0.026
	(0.005)***	(0.003)***	(0.002)***	(0.001)***
Size	0.012	0.000	-0.016	-0.023
	(0.002)***	(0.002)	(0.001)***	(0.001)***
Constant	0.177	0.293	0.018	0.007
	(0.010)***	(0.053)***	(0.005)***	(0.017)***
Tech Dummies	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes
R^2	0.15	0.19	0.80	0.78
N	698,834	1,584,834	698,834	1,584,834

Note:

1. * $p<0.1$; ** $p<0.05$; *** $p<0.01$
2. Robustness Standard Errors are in parentheses

Table 2.10: Coefficient of Post*Abandon based on Years

Patent Grant Year	DV: # of External Citation	DV: # of Patent Classes
1984	-0.012 (0.011)	0.008 (0.004)**
1985	0.017 (0.011)	0.002 (0.004)
1986	0.024 (0.011)	0.009 (0.004)*
1987	0.001 (0.009)	0.004 (0.003)
1988	0.015 (0.009)*	0.013 (0.003)***
1989	-0.012 (0.008)	0.002 (0.003)
1990	-0.028 (0.002)***	0.007 (0.003)**
1991	-0.006 (0.008)	0.021 (0.003)***
1992	-0.000 (0.009)	0.012 (0.003)***
1993	0.034 (0.009)***	0.017 (0.003)***
1994	0.029 (0.010)***	0.018 (0.004)***
1995	0.013 (0.010)***	0.017 (0.004)***
1996	0.034 (0.010)***	0.008 (0.004)**
1997	0.031 (0.011)***	0.003 (0.004)
1998	0.049 (0.008)******	0.013 (0.004)******
1999	0.041 (0.001)***	0.020 (0.003)***
2000	0.064 (0.007)***	0.027 (0.003)***
2001	0.035 (0.005)***	0.030 (0.002)***

Note:

1. * $p<0.1$; ** $p<0.05$; *** $p<0.01$
2. Robustness Standard Errors are in parentheses

Figure 2.1(1): Predictive Margin for External Forward Citations by Year-to-Grant

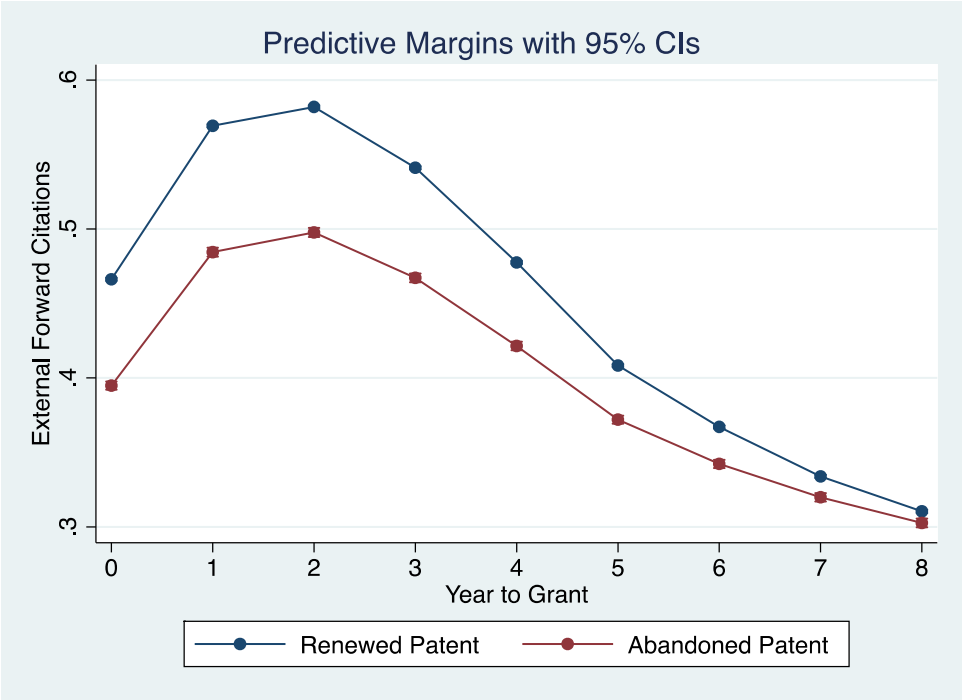
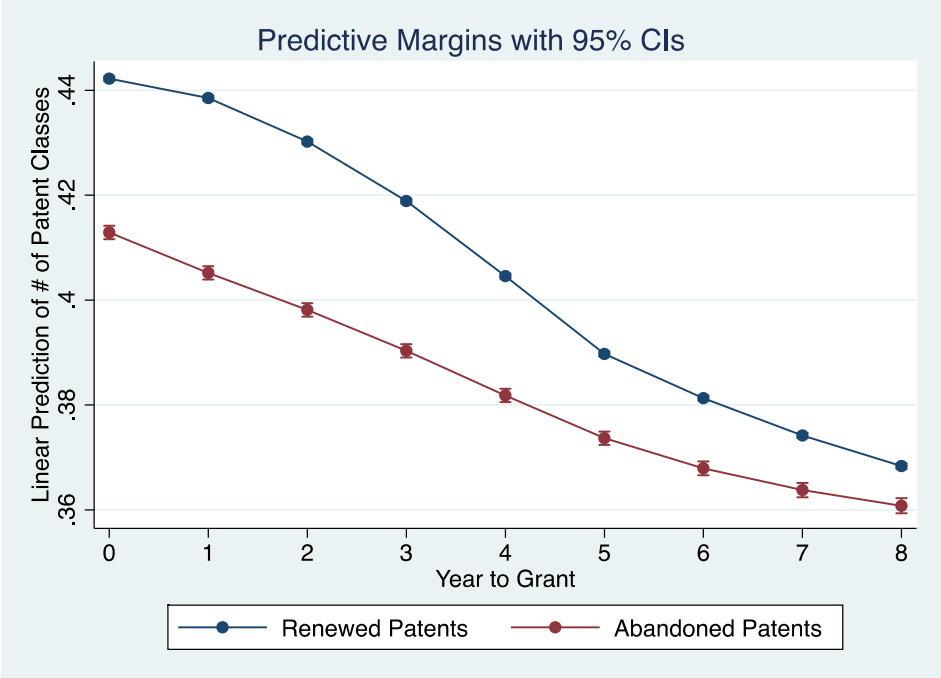


Figure 2.1(2): Predictive Margin for Patent Classes by Year-to-Grant



CHAPTER 3: FIRM'S PATENT ABANDONMENT AND SUBSEQUENT INVENTIONS: KNOWLEDGE SPILLOVER POOL, ABSORPTIVE CAPCITY, OPEN INNOVATION AND COMPLEMENTARY PATENTS

3.1 Introduction

As mentioned in Chapter 1, once the U.S. Patent and Trademark Office (USPTO) issues the patent, the patent holder is required to pay the USPTO three maintenance fees to keep the patent in force. These maintenance fees are due at 3.5, 7.5, and 11.5 years after the issuance of the initial patent. There are also half-year "grace" periods for each window, and the patent holder can still renew the patent by paying the maintenance fee within each grace-period window along with a surcharge for late payment. The patent is abandoned by the patent holder and consequently becomes freely available for the public to use if the patent holder declines paying any of the maintenance fees and/or surcharge at the end of 4^{th}, 8^{th}, and 12^{th} years of issuance. The focal firm's cost of maintaining a single patent is low relative to the large amount of its R&D expenditures in the initial discovery and subsequent development stage (Khanna, Guler, & Nerkar, 2016; Lowe & Veloso, 2015).[18] However, the data show that, from a population of about 1.2 million patents issued by the USPTO, which were applied by firms between 1981 to 2010 (inclusive), firms abandon about 40% of these patents before their statutory expiration date (of 20 years after the priority -- i.e., effective filing -- date), based on firms' decisions to decline paying maintenance fees. Though firms typically abandon a large number of their patents before

[18] For example, based on the April 1, 2018 revision of the USPTO fee schedule, a firm would need to pay $1,600 for the 3 to 3.5 year window, $3,600 for the 7 to 7.5 year window and $7,400 for the 11 to 11.5 year window. The surcharge of late payment (during the "grace" period) is $160. Small entities only need to pay half of these amounts. USPTO Website:

https://www.uspto.gov/learning-and-resources/fees-and-payment/uspto-fee-schedule

their full statutory life, research concerning the consequences to the focal firms of such patent abandonment is limited. This chapter seeks to fill this research gap and explores the focal firm's inventions after its patent abandonment.

When analyzing the focal firm's patent renewal or abandonment decision, research studies often begin with a fundamental (Marshallian) principle of neoclassical economics, which evaluates this decision "at the margin." Applying this principle to the problem at hand, a patent holder will choose to renew the patent when the economic value of maintaining the patent exceeds the cost of renewal. Combining this logic with modern finance theory, Pakes (1986) submits that we can view a patent as a "real option" (Myers, 1977), which gives the patent holder the right (but not the obligation) to pay the renewal fee and maintain its patent in the future. Thus, a profit-maximizing patent holder will only choose to pay the maintenance fee if the sum of the current return plus the economic value of this real option exceeds the renewal fee that the patent holder would pay to the USPTO. Based on this logic, the research literature illustrates that the focal firm typically abandons its patent based on its anticipation of the low economic value of the patent, which is influenced not only by its internal resources and capabilities, but also by external technological developments and market conditions (Liu, Arthurs, Cullen, & Alexander, 2008; Lowe & Veloso, 2015).

However, innovation is typically cumulative (Scotchmer, 1991) and is a highly uncertain and dynamic process, in which its economic value is difficult to measure precisely at a point in time (Kline & Rosenberg, 1986). Therefore, it is possible that the focal firm's abandoned patent will become economically valuable following subsequent technological developments by external inventors/or the focal firm. The 2017 survey by

GreyB Services[19] illustrates the potential strategic importance of this phenomenon, reporting that nearly 35% of the abandoned patents of the focal firms are later revealed by the external inventors (or the focal firm) to have high technological and market value. The extant research typically neglects the potential economic value of the patent created to the focal firm after the patent is abandoned, especially when the focal firm's abandoned patent is later revealed by others to have high technological and market value.

Conventional wisdom suggests that, when the focal firm's abandoned patent is later revealed by others to have high technological and market value, the firm is *defined* to have made an "error" in judgment. The focal firm might lose millions of dollars in patent monetization because of such an "error" in judgment. Moreover, it might lose more economic value when external inventors innovate by freely using the knowledge and technology obtained within the abandoned patent to create patentable improvements, which might block the focal firm from a part of the market that the focal firm originally attempted to capture, and thus impede the focal firm's subsequent innovation. Thus, business consultants normally recommend that the focal firm should not abandon its patents, or evaluate carefully the economic value of the patent by exploring more usability of its patent to avoid the mistakes of abandoning a patent with high technological and market potential. However, in the business world, major technology giants such as IBM, Samsung, and HP abandon large amounts of their patents, despite the fact that external inventors may later reveal that these patents have high technological and market value. Given the potential high risk of abandoning valuable patents and the relative low cost of

[19] See https://www.greyb.com/throwing-away-million-dollar-patents/

maintaining a patent, the puzzle is: why do firms abandon these patents with high technological and market potential?

This chapter relaxes the zero value of abandoned patent assumption in the neoclassical economics model and examines conditions that can enable the focal firm to achieve positive value capture through abandoning its patent. Instead of viewing the focal firm's abandoning a patent, which is later revealed to have high technological and market value as always leading to poor consequences for the focal firm, this chapter offers an alternative explanation of why the focal firm might achieve positive economic value capture through abandoning such a patent. Due to the focal firm's bounded rationality (Simon, 1947; Williamson, 1975), and limited resources and capabilities (Penrose, 1959), it has limited search in both exploitation and exploration of its patent (Cyert & March, 1963; March, 1991). Thus, the focal firm is incapable of, or faces high costs in searching and acquiring a comprehensive set of knowledge required for subsequent development of its patent. However, if the focal firm abandons the patent, it can open invention development to more external inventors to search collectively for new knowledge in subsequent development of the focal firm's abandoned patent, which might go beyond what the focal firm could do on its own when holding its patent. Thus, the technological or market value of the focal firm's abandoned patent is more likely to be realized with more external inventors' involvement in subsequent inventions development, which is driven by the focal firm's patent abandonment. Moreover, while the focal firm can abandon the patent for knowledge generation and value creation, it can also learn from these external inventors and develop new inventions through recombining external inventors' patents in the knowledge spillover pool with its own novel insights (Kogut & Zander, 1992) for value

appropriation. The focal firm can develop inventions comparatively quickly and efficiently because it often spends large amounts of resources in creating and developing the patent, which can contribute to its strong absorptive capacities concerning the abandoned patent, as well as patents within the knowledge spillover pool (Cohen & Levinthal, 1990).

As mentioned in Chapter 2, the focal firm's patent abandonment can reduce the costs of external inventors in using these abandoned patents in subsequent innovation and thus provide them opportunities to create (patentable) improvements that build on the focal firm's abandoned patent. Thus, Chapter 2 concludes that external inventors could benefit from the focal firm's patent abandonment. As an extension, this chapter further explores whether the *focal firm* can also obtain positive value capture from its patent abandonment. To the best of my knowledge, before my empirical study here, no study in the extant literature has examined the possibility that the focal firm can achieve positive value capture through abandoning its patents by learning from the knowledge spillover pool that is created by its patent abandonment.

In this chapter, I submit that the focal firm could substantially benefit from abandoning its patent if this (strategic) move can motivate potential external inventors to create a more valuable knowledge spillover pool than would exist if the focal firm's patent were renewed, and this firm can then successfully develop more valuable cumulative inventions than the original abandoned patent through learning from these external inventors within this knowledge spillover. That is, the focal firm can create new (patentable) inventions through subsequent knowledge re-combination (Kogut & Zander, 1992), which entails external inventors' patents within the knowledge spillover pool created through the focal firm's patent abandonment, along with novel insights that the

focal firm then contributes in producing subsequent valuable patents. For the purpose of contributing to both strategic management theory and practice, this chapter highlights that the focal firm may achieve positive value capture, either by an "emergent strategy" (Mintzberg, 1978) or through "strategic foresight" (Marcus, 2009). A "strategy" can emerge as an unintended outcome in which the focal firm vicariously learns from the external inventors' subsequent development of its abandoned patent and develops more subsequent inventions that build on knowledge generated by these external inventors. Another possibility is that the focal firm has the foresight to recognize that the inventions are not necessarily a zero-sum game, but rather can be a positive sum game. Thus, in this context, while the external inventors can gain from the focal firm's abandoned patent, the focal firm deliberately attempts to increase its own economic rents from its inventions by abandoning its patents.

The research literature in strategic management, following closed innovation principles, typically emphasizes mechanisms that help prevent spillovers and imitation to secure a firm's value appropriation and maintain its sustainable competitive advantage (Barney, 1991; Peteraf, 1993). However, such deterrence-based appropriability might sacrifice economic value creation, especially when considered from the perspective of an innovation ecosystem (Adner & Kapoor, 2010). Therefore, many recent research studies have begun to investigate a fuller and richer view, embodying at least in part, open innovation principles (Chesbrough, 2003) that the focal firm sometimes strategically decreases its efforts at deterring imitation and knowledge spillovers to increase its value creation and value capture (Alexy, West, Klapper, & Reitzig, 2018; Hayter & Link, 2018; McEvily, Das, & McCabe, 2000; Polidoro & Toh, 2011). Bob Cater (Senior Vice President

of Automotive Operations at Toyota Motor) states: "At Toyota, we believe that when good ideas are shared, great things can happen. … By eliminating traditional corporate boundaries, we can speed the development of new technologies and move into the future of mobility more quickly, effectively and economically."[20] The focal firm's knowledge sharing provides opportunities for its value-creating complementarities (Milgrom & Roberts, 1990; Teece, 1986; Toh & Miller, 2017) and enable the focal firm to identify potential strategic alliance partners and knowledge in its future technology development (Phene & Tallman, 2014). The focal firm can better learn from external firms' activities in developing their own technologies and re-absorb the knowledge that has been leveraged externally, which facilitates its dynamic capabilities and its subsequent future innovation performance and stock market performance (Alnuaimi & George, 2016; Belenzon, 2012; Yang, Phelps, & Steensma, 2010). Building on previous research literature on learning from knowledge spillovers, this chapter focuses on a specific type of knowledge spillover, which the focal firm creates via its patent abandonment.

This chapter examines conditions enabling a focal firm to achieve subsequent cumulative inventions that build on patents within the knowledge spillover pool created through its patent abandonment. I submit that the focal firm's patent abandonment can motivate external inventors with relevant knowledge to self-select to work on the area of the abandoned patent, which transforms the focal firm's own limited search in exploitation and exploration of its patents into external inventors' collective search. The transformation of search pattern in subsequent invention development can facilitate knowledge generation

[20] See http://toyotatoday.com/news/royalty-free.htm

and entail lower costs in search for such development not only for the external inventors, but ultimately for the focal firm as well. The focal firm can learn from these external inventors to improve its subsequent inventions in a more cost-effective manner. The more valuable knowledge created through the external inventors' collective search and the more external inventors contributing in collective search for development of the focal firm's abandoned patent, the more effective this collective ("wisdom of crowds") search is likely to be while maintaining low cost for the focal firm. Building on the knowledge obtained through this collective search, the focal firm is more likely to achieve subsequent inventions through learning from the knowledge spillover pool created through its patent abandonment. Furthermore, the focal firm's absorptive capacity concerning patents within knowledge spillover pool, prior experience in leveraging external sources of innovation, and holding of complementary patents may enhance its learning efficiency and effectiveness.

In this chapter, I seek to contribute to three important conversations in the extant research literature. First, I seek to contribute to the patent renewal literature by linking this research with the open innovation literature (von Hippel & von Krogh, 2003). This chapter suggests that the focal firm's patent abandonment is not only a strategic choice about whether the focal firm would like to continue or terminate a certain line of research, but also a choice between relying on its own internal search vis-à-vis relying on external collective search for subsequent development of its invention. This chapter aims at exploring how the focal firm can use patent abandonment to balance value creation and value capture through facilitating cumulative inventions, which is less explored in the current literature (Somaya, 2012). To the best of my knowledge, I contribute the first

empirical study in the literature that examines the possibility that the focal firm can achieve value capture through (strategically) abandoning its patents by learning from the knowledge spillover pool that the focal firm creates by its patent abandonment.

Second, I seek to contribute to the extant organizational learning literature, which has shown that firms can learn from their own and their competitors' different types of successes and failures (Eggers, 2012; Katila & Chen, 2008). For example, Khanna, Guler, and Nerkar (2016) interpret a firm's patent abandonment decision before the legally allowed 20-year period as an indicator of self-admitted small failures in experimentation and suggest that firms can obtain (timely) feedback from these failures to improve their future innovation performance. In this chapter, however, I offer an alternative (strategic) interpretation of a firm's patent abandonment. Khanna, Guler, and Nerkar (2016) suggest that these small failures can encourage the focal firm to experiment internally in searching for the causes of these failures before it makes further investment decisions. This chapter maintains that the focal firms can also obtain feedback externally, and can gain from other firms' collective insights that are enabled due to the focal firms' relatively narrower knowledge base.

Third, I seek to contribute to the knowledge spillover literature, which has addressed the importance of the focal firm's capability in internalizing knowledge spillovers from its own innovation on its value capture (Belenzon, 2012; Jaffe, Trajtenberg, & Fogarty, 1993). The extant literature has discussed the determinants of the focal firm's learning from knowledge spillovers from its own original invention in its subsequent inventions. Factors include characteristics of the: (i) originators and recipients (Operti & Carnabuci, 2014); (ii) technology in the patent (Alnuaimi & George, 2016); and (iii)

spillover knowledge pool (Yang, Phelps, & Steensma, 2010). As an extension, I focus on the focal firm's learning from a special type of knowledge spillover created through the focal firm's abandoning its patent. I further discuss how factors, such as: (a) the focal firm's absorptive capacity concerning patents within the knowledge spillover pool; (b) its prior reliance on open innovation; and (c) its ownership of complementary patents influence the focal firm's learning from the knowledge spillover pool of its patent abandonment.

3.2 Theory and Hypotheses

Patent Abandonment, Collective Search, and Value Creation

According to the resource-based approach, a resource can become more economically valuable when more "services of the resources" are discovered or created (Foss & Foss, 2005; Kim & Mahoney, 2010; Penrose, 1959). Modern technologies are dynamic and often overlap multiple fields and application areas.[21] For example, virtual reality -- a branch of computer technology -- has applications in several major industries including the military, health care, and entertainment industries. Therefore, to realize more economic value of its patent, the focal firm should look beyond its actual competition and explore more usability of its patents in areas that it might not be as familiar. The focal firm can either conduct its own boundary-spanning search (Laursen, 2012) or, as the current research has emphasized, abandon its patent to enable external inventors' collective search for exploiting and exploring more services/ applications of its patent.

Behavioral economics suggests that the focal firm, being boundedly rational, finds it almost impossible to develop the full potential of its patent if it did not enable open innovation (Chesbrough, 2003). An invention is described as an outcome of a novel

[21] See https://www.greyb.com/patent-portfolio-strategy-filing-patent-continuations/

recombination of existing elements of knowledge (Fleming, 2002), or the reconfiguration of the ways in which knowledge elements are linked (Henderson & Clark, 1990). Through invention, not only the knowledge within the focal firm, but also knowledge outside of the firm can become important determinants for the focal firm's invention performance and its profitability (Allen, 1977; Burns & Stalker, 1961). Third-party knowledge and inventions can play a key role in the development of the abandoned patent, especially for some "platform" technologies (Lichtman, 2000). To develop further its patent, the focal firm needs to conduct internal and external search consistently (Chesbrough, 2003; Landau & Rosenberg, 1986).

If the focal firm holds the patent to have exclusive rights over the use of its technology, its search in exploitation and exploration of the invention development is posited to be bounded, in the sense that it is more likely to restrict its attention within its familiar area (Cyert & March, 1963; Ocasio, 1997), and conduct intelligent searches where its routines, cognitive framing, and absorptive capacity enable its effective assessment of alternatives and consequences (Afuah & Tucci, 2012; Cohen & Levinthal, 1990). The costs of conducting distant search are usually high, because it requires the focal firm to acquire new resources and capabilities, which lowers the focal firm's expected economic profitability (Afuah & Tucci, 2012). The focal firm can also collaborate with external inventors for knowledge exploitation and exploration through standard collaboration mechanisms (such as license or cross-license agreements). To leverage these mechanisms effectively, the focal firm first needs to possess the capabilities to identify and evaluate the potential external inventors with relevant knowledge, which is restricted by the focal firm's knowledge, experiences, and absorptive capacity. In addition, the focal firm usually needs

to negotiate a contract ex ante with these potential external inventors, which can create high transaction costs due to the incomplete contracting problems (Williamson, 1996). Further, some contract terms, such as a "grant-back" clause (Leone & Reichstein, 2012) or an exclusivity clause (Somaya, Kim, & Vonortas, 2011), which are used by the focal firm as transactional safeguards, can limit external inventors' creation of cumulative inventions.

Moreover, the existence of cumulative inventions cannot be taken for granted. Potential external inventors may need substantial development (sunk) costs before they can bargain for a license with the focal firm. If the patent protects the original invention, and consequently, these potential external inventors would anticipate being held up in the bargaining stage, they might decide to forego cumulative inventions altogether at the beginning (Bar-Gill & Parchomovsky, 2003), especially when the holders of relevant patents are fragmented (Heller & Eisenberg, 1998; Huang & Murray, 2009; Ziedonis, 2004). However, once the focal firm abandons the patent, it becomes available in the public domain and is freely available to use. As is shown in Chapter 2, the removal of the intellectual property rights can facilitate knowledge generation by motivating inventors self-selecting to work on the technology and to explore alternative commercialization approaches to realize more technological and market value of the patent (Galasso & Schankerman, 2015; Murray, Aghion, Dewatripont, Kolev, & Stern, 2010). Without the focal firm's patent abandonment, the individuals and organizations with relevant technological knowledge may not even be revealed to the focal firm. It is impossible for the focal firm to acquire or contract for the requisite knowledge if they do not know where the knowledge is located and who can develop the technology (Felin & Zenger, 2014).

Further, while the focal firm abandons the patent for knowledge generation and economic value creation, it can also develop new (patentable) inventions through subsequent knowledge recombination (Kogut & Zander, 1992) for value appropriation by learning from the knowledge spillover pool created by these potential external follow-on inventors. The focal firm often spends large amounts of resources in invention creation and development stage, which can contribute to its strong absorptive capacity (Cohen & Levinthal, 1990) and can provide complementary assets (Teece, 1986). Therefore, the focal firm can become familiar with the abandoned patent, as well as patents in the knowledge spillover pool derived from its abandoned patent comparatively quickly and efficiently (Yang, Phelps, & Steensma, 2010), which facilitate the focal firm's subsequent learning from this spillover pool. The extant literature typically corroborates that the focal firm's capability in managing knowledge spillover created from its own inventions impacts whether the focal firm can capture value from its own knowledge spillovers (Agarwal, Audretsch, & Sarkar, 2007; Belenzon, 2012). Table 3.1 provides a review of the research literature on factors that influence the focal firm's learning from its own knowledge spillovers. This chapter posits that the focal firm's patent abandonment can create positive economic value for the focal firm if it can develop more new inventions through learning from the valuable knowledge spillover pool created through its patent abandonment.

This chapter does not suggest that all abandoned patents can realize greater technological and market value based on open innovation principles. Indeed, there are many patents that have very low quality and cannot create sufficient economic value, which can be captured by the focal firm. Under such circumstances, there will be less knowledge generated and fewer external inventors joining the knowledge spillover pool to develop

these patents even after they are abandoned. Rather, our hypothesis is that at least *some* abandoned patents may realize more of their market or technological value after they are abandoned. For these patents, the focal firm's patent abandonment can provide more opportunities for it to learn from these external inventors and create its own inventions that build on patents within the knowledge spillover pool (Alexy, George, & Salter, 2013; Belenzon, 2012; Yang, Phelps, & Steensma, 2010).

Knowledge Spillover Pool, Collective Search and the Focal Firm's Subsequent Inventions

Innovation is a complex and uncertain process, which requires feedback loops among the different stages of the process (Kline & Rosenberg, 1986; Peterson, Rotolo, & Leydesdorff, 2016). The focal firm typically abandons the patent based on current technological development and market conditions. However, it is usually difficult for the focal firm to measure the exact economic value of the technology in the patent at the decision making point. The focal firm's patent abandonment reduces the costs of external inventors in using the abandoned patent for innovation, which results in a creation of a larger and broader knowledge spillover pool (Bessen, 2008; Bessen & Maskin, 2009). Thus, the abandoned patent can become more valuable to the focal firm after the subsequent development by external inventors (Kline & Rosenberg, 1986). Conventional wisdom suggests that the focal firm would lose millions of money in patent monetization when the external inventors create a high quality knowledge-spillover pool after focal firm's patent abandonment. Therefore, the focal firm is usually counseled to not abandon its patent even if it lacks the resources and capabilities to develop further its patent internally and/or through market for technology.

However, this chapter points out a potential benefit of the focal firm's patent abandon-ment. This chapter maintains that a higher quality knowledge spillover pool can also provide a focal firm with a greater knowledge base for screening and selecting, which increases the amount of useful feedback it could get from external inventors to further develop its original abandoned patent and improve its future cumulative inventions (Operti & Carnabuci, 2014; Yang, Phelps, & Steensma, 2010). A research scientist, who I interviewed, from a semiconductor company states the following, which corroborates that they would learn from their competitors in terms of further development of their prior abandoned projects:

> "*We have regular team meetings weekly and monthly to go through every failed project and summarize these failed projects to see what we could learn from these failures……In our weekly meeting, we would also discuss the progress of our competitors. We will adjust ours based on their failures and successes [of similar projects]*. "

Furthermore, the focal firm often spends large amounts of resources in the initial discovery stage and subsequent development stage, which can contribute to its strong absorptive capacity (Cohen & Levinthal, 1990). Therefore, the focal firm can become comparatively quickly and efficiently familiar with the patents in the knowledge spillover pool derived from its abandoned patent (Yang, Phelps, & Steensma, 2010). In our interview, the research scientist mentioned:

> *"[If someone else finds a new usage of our patent,] we might first wait and see to let them test the market first. If it is promising, we could easily jump back in [the prior abandoned project] and take over the market. We have*

a lot of advantages over them, so it's easy for us to take the market share from them. We have economies of scale, good quality control system, mature production line, more employees and large teams. Again, we could wait to let them test the market."

The focal firm is then capable to learn from the spillovers of its own patent, even when it abandons its patent. This logic leads to the following hypothesis:

> *H1: An increase in the quality of the knowledge spillover pool leads to an increase in the focal firm's cumulative inventions that build on patents within this spillover pool.*

The Focal Firm's Search Path, Internal Usage and the Focal firm's Subsequent Inventions

This chapter considers the focal firm's patent abandonment as a potential alternative strategy to attempting its own broad (and distant) search. The focal firm can use its patent abandonment to motivate external inventors conducting collective search to complement its own search strategy. However, the focal firm cannot capture sufficient economic value from its patent abandonment if the focal firm lacks resources and capabilities to learn effectively and efficiently from the valuable knowledge spillover pool created by external inventors after the focal firm's patent abandonment.

Effective and efficient learning from the knowledge spillover pool is enhanced by the focal firm's superior absorptive capacity concerning its abandoned patent and subsequent inventions that build on this abandoned patent, which is driven by its accumulated stock of related knowledge (Cohen & Levinthal, 1990; Fabrizio, 2009). The focal firm's knowledge search paths in the initial invention creation stage can influence its absorptive capacity required in subsequent learning from the knowledge spillover pool. The required knowledge in subsequent development of the invention created through the

focal firm's explorative search paths might be quite different from the focal firm's existing knowledge base, which requires the focal firm to conduct more distant search for new capabilities and technological knowledge (Levinthal & March, 1993; Lowe & Veloso, 2015; March, 1991). Levinthal and March (1993) show that the focal firm's knowledge search path associated with exploration beyond this focal firm's border in early creation stage are more likely to fail when it conducts its own search. This chapter suggests that the focal firm lacks the absorptive capacity to learn from external inventors' subsequent develop-ment of its abandoned patent created through explorative search path. Thus, though the external inventors' collective search after the focal firm's patent abandonment may realize more the technological and market value of the abandoned patent, the focal firm's inferior absorptive capacity will prevent it from capturing value created through the focal firm's patent abandonment. This logic leads to the following hypothesis:

> *H2: The positive relationship between the quality of the knowledge spillover pool and the proportion of the focal firm's cumulative inventions that build on patents within the knowledge spillover pool will be weaker if this abandoned patent is derived from the focal firm's explorative search paths in the initial invention creation stage.*

The focal firm's familiarity to the patent will not only be influenced by its search path in the initial invention creation stage, but also by its subsequent internal usage of the patent before it is abandoned. In the subsequent development stage, the focal firm will gain more familiarity to the knowledge in the patent through more subsequent internal usage of that patent (as measured by forward self-citations) before it is abandoned. Repeatedly drawing knowledge from a given patent is important because it increases a firm's mastery of the scientific and engineering knowledge of this particular patent, which results in a better understanding of causal links and absorption of ideas, solutions, and processes that are described in the patent (Nerkar & MacMillan, 2003). Further, the process also leads to

the creation of competencies related to the patent in multiple technological areas. This logic leads to the following hypothesis:

> *H3: The positive relationship between the quality of the knowledge spillover pool and the proportion of the focal firm's cumulative inventions that build on patents within the knowledge spillover pool will be stronger if the focal firm's internal usage of its abandoned patents are higher before they are abandoned.*

Prior Reliance of External Sources of innovation and the Focal Firm's Subsequent Inventions

To capture economic value from its patent abandonment strategy, the focal firm needs to obtain, integrate, and commercialize external sources of inventions created through its patent abandonment. The process becomes complex when involving crowdsourcing innovation because it requires the focal firm to interact with multiple external inventors at different stages of innovation (Afuah & Tucci, 2012; West & Bogers, 2014). Felin and Zenger (2014) submit that culture and organization structure are different between closed innovation and open innovation systems. Furthermore, the focal firm needs to possess sufficient resources and capabilities in leveraging the external sources of innovation to create more inventions that build on patents within the valuable knowledge spillover pool created through its patent abandonment (West & Bogers, 2014). When the focal firm's prior innovation relies more on external sources of inventions, it typically can create organization structure and culture that fit the open innovation system and accumulate more related resources and capabilities in leveraging external sources of inventions (Cohen & Levinthal, 1990). Thus, when the focal firm relies more on external sources of inventions in its prior inventions, it will be more likely to abandon patents for value creation and it could be more capable to capture value from its patent abandonment when the knowledge

spillover pool created through its patent abandonment becomes more valuable. Thus, the above logic leads to the following hypothesis,

> *H4: The positive relationship between the quality of the knowledge spillover pool and the proportion of the focal firm's cumulative inventions that build on patents within the knowledge spillover pool will be stronger if the focal firm relies more on external sources of inventions in its prior invention activities.*

The Focal Firm's Complementary Patents and the Focal Firm's Subsequent Inventions

In addition to the abandoned patent, there are also some complementary patents, which are typically recombined with the abandoned patent to create valuable subsequent cumulative inventions. While the focal firm seeks to learn from the knowledge spillover pool that has been built on its initial abandoned patent, it might face potentially important constraints because it is more likely to infringe on the patents in the knowledge spillover pool if the focal firm wants to create new inventions that build on these patents within the knowledge spillover pool. These constraints can be mitigated if the focal firm owns some of the active complementary patents. In such a situation, the focal firm will have more bargaining power and is less likely to be blocked by these external inventors holding patents in the knowledge spillover pool during the subsequent invention process due to mutual holdup threats (Somaya, 2003). Teece (1986) submits that when the property rights regime is weak, the focal firm may need to rely more on controlling complementary assets to increase the likelihood and magnitude of the captured value from its intellectual property in the innovation process. In addition, Fosfuri, Giarratana, and Luzzi (2008) maintain that the pre-existing assets affect the direction, as well as the pace of change and adaptation of the firm. In this context, though the focal firm abandons its patent, the focal firm can still

obtain value capture in subsequent innovation through holding more patents that are complementary. This logic leads to the following hypothesis:

> *H5: The positive relationship between the quality of the knowledge spillover pool and the proportion of the focal firm's cumulative inventions that build on patents within the knowledge spillover pool will be stronger if the focal firm holds more patents that are complementary.*

To summarize, Figure 3.2 shows the hypotheses developed within the current research. In the next section, I will discuss the empirical methodology used to test these hypotheses.

3.3 Methodology

Sample and Data

Following the extant empirical literature (Hoetker & Agarwal, 2007; Jaffe, Trajtenberg, & Fogarty, 1993; Yang, Phelps, & Steensma, 2010), I use patent citations to track the focal firm's inventions and as indicators of the external inventors' subsequent inventions in the knowledge spillover pool. Patent applicants are required by law to list relevant citations to prior patents (including those abandoned patents) in their applications, which delimit the scope of the property rights awarded by the patent (Galasso & Schankerman, 2015; Hall, Jaffe, & Trajtenberg, 2001). For example, if patent B cites patent A, it implies that patent A represents a piece of previous existing knowledge upon which patent B builds, and over which patent B cannot have a claim. Therefore, patent citations can represent reliable and observable indicators of knowledge spillovers (Hoetker & Agarwal, 2007; Yang, Phelps & Steensma, 2010). Though patent examiners can remove or add some citations to patents, which might make it noisy to use patent citations as a measure of knowledge spillovers, there is no evidence showing that such noise in the data

would bias the empirical estimation of the observed knowledge flow (Jaffe, Trajtenberg, & Fogarty, 1993; Yang, Phelps, & Steensma, 2010).

In this chapter, I focus on the semiconductor patents (NBER technological sub-categories code = 46). I consider a single technological area to mitigate problems related to unobserved heterogeneity (Ardito, Petruzzelli, & Panniello, 2016). I choose the semiconductor patents for the following reasons. First, technologies are cumulative and tend to be complex in the semi-conductor area. Therefore, the subsequent development of a patent typically requires the use of a broader knowledge base, coming from many scientific disciplines and industry sectors. Hence, the subsequent exploitation and exploration of the focal firm's patent have great impact on the realization of the economic and technological value of this patent. Second, patent abandonment is a major problem for the focal firm's decision-makers in the semiconductor area. Firms typically spend millions of dollars every year to prune their patent portfolios in semiconductor area. However, nearly 35% of the focal firms' abandoned patents are revealed to have high technological usefulness by external inventors. Thus, examining the impact of the focal firm's abandoned patents on its subsequent innovation performance in the semiconductor area allows for both academic rigor and practical relevance.

The empirical work in this chapter is based on three data sets: First, I collect a list of abandoned patents in the semiconductor category from USPTO Official Gazette, which lists expired patents weekly. Second, I obtain patent-level data from NBER patent dataset and Indiana & MIT patent database. Third, I use Compustat to obtain the financial data of each firm and merge the dataset with the patent level data. To minimize left- and right-censoring regarding the collection of patent data and to ensure access to firm-level financial

data, I limit the sample to the patents that are abandoned between 1986 and 2001 (inclusive). Because I examine the effects of the focal firm's patent abandonment on its subsequent invention performance, I only keep firms in my sample that are active in patenting and patent abandonments and survive more than 10 years after it abandons the patent. Therefore, I remove those firms that do not patent or abandon their patents for more than 5 years between 1986 and 2001 (inclusive). I also limit the sample firms to public firms to ensure the availability of financial data. An additional reason for the non-inclusion of those firms that are not publicly traded is based on evidence showing that many non-public organizations and individuals abandon their patents because of their lack of resources in patent management.[22] Through this process, I identify 1030 patents in the final sample belonging to 69 firms.

Dependent variable

I follow the steps proposed by Alnuami and George (2016) to operationalize the know-ledge spillover pool created through the focal firm's patent abandonment. For each of the focal firm's patent abandoned in year *t*, I identify patents that are applied by external inventors and cite this abandoned patent during year *t+1* and year *t+5* (inclusive). The collection of such patents forms the knowledge spillover pool of the focal firm's abandoned patent, which is illustrated in Figure 3.1.

I measure *Cumulative Inventions* as the number of successful applied patents during year *t+6* to *t+10* (inclusive) that cite the patents within the knowledge spillover pool. The dependent variable is the citation-weighted proportion of *Cumulative Inventions* that belong to the focal firm during year *t+6* to *t+10* (inclusive). The dependent variable is a

[22] See https://patinformatics.com/are-small-entities-more-likely-to-abandon-us-granted-patents-than-large-ones/

share rather than a count of citations, which captures the focal firm's superior capabilities in learning from the knowledge spillover pool and generating inventions that build on the patents within the knowledge spillover pool.

Independent Variables and Moderators

I use the number of forward citations that a patent receives as a measure of patent quality (Trajtenberg, 1990). For each abandoned patent, I identify all the patents within the knowledge spillover pool. I then identify all the external forward citations of this stock of patents received by 2010[23]. The *Quality* of knowledge spillover pool is measured as the number of these forward citations. I divided this variable by 1,000 to reduce the scale.

Following Lowe and Velosso (2015), I measure the focal firm's *Exploratory Search Paths* in creating the focal firm's patent as the percentage to which a patent draws on knowledge outside the focal firm's existing knowledge base. Similarly, following Benner and Tushman (2002), and Lowe and Velosso (2015), this chapter defines the knowledge outside the focal firm's existing knowledge base as backward citations made to the patent, which are neither one of the firm's own patens, nor a patent cited previously by the focal firm in another firm's patents.

I use the *Internal Usage* to measure the focal firm's subsequent internal development of its abandoned patents. For each focal patent that has an assignee code,[24] I first define self-citations as patents that have the same assignee code with the focal patent and that cite the focal patent. Second, I count the number of self-citations that the focal

[23] I exclude the self-citations for endogeneity concern. I also conduct robustness check by including the self-citations into the independent variable. The results are mostly the same.

[24] I use the "lpermno" code in the *Indiana & MIT* patent database to identify the each patent assignee.

patent receives 4-years before it is abandoned. The construct *Internal Usage* is measured as the ratio of the focal firm's self-citations of the abandoned patent to the total citations of the patent.

I define the focal firm's prior reliance on external sources of innovation *(i.e., Open Innovation)* as the extent to which the focal firm's innovation activities are based on external knowledge. I define external knowledge as backward citations made to the focal firm's overall patent stock that are not belong to the focal firm's own patents.

Following Toh and Miller (2017), I define the complementary patents as those patents that are jointly cited with the focal firm's abandoned patent, and belong to different patent classes with the focal firm's abandoned patent. The *Self-Owned Complementary Patents* construct (*Self-Owned Comp.*) is measured as the percentage of complementary patents of the abandoned patent that is owned by the focal firm. I only keep the active complementary patents and remove those that are expired or abandoned by the focal firm.

Control Variables

I include several knowledge spillover pool-level, firm-level, and patent-level control variables that could influence the *Focal Firm's Subsequent Cumulative Inventions*. I also include year-dummies and industry-dummies in each model to control for time-and industry-specific unobservable factors.

Number of External Inventors

The *Number of External Inventors* that are within the knowledge spillover pool, would influence the value of this spillover pool, and thus influence the focal firm's subsequent learning and value capture from this spillover pool. On the one hand, more external inventors in the knowledge-spillover pool can bring more diversified knowledge

to enrich focal firm's existing knowledge base and enable the focal firm to envision new applications and combinations for its existing technology. If the focal firm has sufficient resources and capabilities in leveraging these external sources of innovation, such transformation of search pattern enables the focal firm to enjoy more benefits of distant search for subsequent innovation without incurring as much costs (Afuah & Tucci, 2012). Thus, building on the knowledge obtained through collective search, the focal firm is likely to develop more inventions to capture value through its patent abandonment. On the other hand, anti-commons theory suggests that the focal firm's cost of knowledge acquisition will significantly increase when the required knowledge is within fragmented intellectual property rights. When the patents within the knowledge spillover pool are distributed to more external inventors, the focal firm's capabilities in integrating inventions within the knowledge spillover pool will be reduced. I measure the construct as the total number of assignees (excluding the focal firm) for the patents in the knowledge spillover pool.

Knowledge Similarity

Knowledge Similarity refers to the similarity between the knowledge spillover pool and the focal firm's existing knowledge base. From the knowledge generation perspective, successful knowledge generation in a collective search context that is enabled by the focal firm's patent abandonment will be positively associated with increasing knowledge distance between the knowledge spillover pool and the focal firm's existing knowledge base (Jeppesen & Lakhani, 2010). However, from a perspective of absorptive capacity, the focal firm is less likely to learn from the knowledge spillover pool if the knowledge contains in the spillover pool is more different from the focal firm's existing knowledge

base (Yang, Phelps, & Steensma, 2010). Following Yang and colleagues (2010), an index that is originally developed by Jaffe (1986) is used as follows:

$$Knowledge\ Similarity = \sum_j d_j\, e_{ij} / [\left(\sum_j (d_{ij})^2\right)^{\frac{1}{2}} \left(\sum_j (e_{ij})^2\right)^{\frac{1}{2}}]$$

where d_{ij} represents the number of patents of patent class j within the knowledge spillover pool create after patent i is abandoned, and e_{ij} represents the number of patents of patent class j that are applied by the focal firm.

Current Ratio

The *Current ratio* is used to reflect the availability of the focal firm's slack resources, which could enhance its innovation capabilities, and learning from the knowledge spillover pool of the abandoned patent (Yang, Phelps, & Steensma, 2010). I calculate the *Current Ratio* as current assets over current liabilities.

Firm Size

Prior research studies have shown that a firm's size will influence both the patent abandonment decision and learning from the knowledge spillover pool. On the one hand, a smaller firm is more likely to rely on external search in developing their innovation due to a lack of resources for subsequent exploitation and exploration of its patent. On the other hand, a smaller firm may lack absorptive capacities to capture economic value through developing new patents through learning from the knowledge spillover pool that is created by its abandoned patent. I apply the number of employees to measure *Firm size*. I divided this variable by 10^6 to reduce the scale.

Firm Diversification

A technologically diversified firm has a broader knowledge base and may be more likely to learn from the knowledge spillover pool in its subsequent invention. However, it is also possible that a technologically diversified firm will have less incentive to rely on external inventors' subsequent development of its technology due to its superior internal search capabilities. Following Yang and colleagues (2010), I measure Firm Diversification in year t-1 as the Herfindahl-type index:

$$Firm\ Diversification_{it-1} = [1 - \sum_{j} \left(\frac{N_{jit-1}}{N_{it-1}}\right)^2] \times \frac{N_{it-1}}{N_{it-1} - 1}$$

where N_{jit-1} represents the number of patents of patent class j in firm i's patent stock at year $t-1$, and N_{it-1} represents the total number of patents that are in firm i's patent stock at year $t-1$.

Patent Scope

Prior research studies have shown that broader patents will tend to block more subsequent inventions that are derived from those patents (Huang & Murray, 2009). As a result, the focal firm's abandonment of its broader patent is more likely to generate a larger knowledge spillover pool, which makes it more likely that the focal firm will learn. Following Huang and Murray (2009), I measure the scope of each patent as the number of patent classes that are assigned to that patent.

Backward Citations

Backward citations reflect the technology maturity of the patent. Technology maturity has two competing impacts on learning from the knowledge spillover pool. A patent that contains more mature technology is easier to understand, which facilitates subsequent learning. However, the patent that contains mature technology is less uncertain

when it is abandoned, which lowers the focal firm's incentive to track the development of its abandoned patent.

Abandon Stage

As mentioned in Chapter 2, in the United States, a patent holder is required to pay three maintenance fees after the issuance of the initial patent. The longer the firm holds the patent, the more familiar the focal firm is for the abandoned patent, which contributes to the high absorptive capacity. However, at the same time, there would be fewer opportunities for the focal firm to learn from the knowledge spillover pool. I add two control variables, which is Abandon Stage_2nd and Abandon Stage_3rd to control for different stages of the focal firm's patent abandonment.

Empirical Results

In all the econometric models, I include year- and firm-dummies to control for time and firm-specific unobservable factors. Table 3.4 presents descriptive statistics and the correlation matrix for all of the variables. To assess potential problems of multicollinearity, I calculate variance inflation factors (VIFs) for the independent and control variables. VIF values for the full model range from 1.07 to 8.85 with the mean VIF of 4.47. A VIF below 10 indicates that a multicollinearity problem is not likely to be an issue in my data (Wooldridge, 2002). Table 3.5 reports the regression results with *CI* as dependent variable.

Table 3.5 provides the empirical results. Model 1 includes all of the control variables. Model 2 introduces the variable *Quality* of knowledge spillover pool to test Hypothesis 1. As shown in Model 2, the *Quality* of the knowledge spillover pool has a significant and positive effect on the proportion of *cumulative inventions* that belong to the focal firm ($\beta_{CI} = 0.096, P_{CI} < 0.01$). This empirical result corroborates Hypothesis 1.

Model 3 incorporates the interaction term of the *Quality* of the knowledge spillover pool and the focal firm's *Explorative Search Paths* to test Hypothesis 2. Hypothesis 2 suggests that the extent of *Explorative Search Paths* in creating the abandoned patent significantly and positively moderates the relationship of *the Quality of the knowledge spillover pool* and the proportion of focal firm's cumulative inventions that build on the patents within the knowledge spillover pool. The interaction term is significantly negative in model specification 5 ($\beta_{CI} = -0.109, p_{CI} < 0.05$). Thus, Hypothesis 2 is corroborated.

Model 4 incorporates the interaction term of the *Quality* of the knowledge spillover pool and the focal firm's *Internal Usage* of the abandoned patent to test Hypothesis 3. Consistent with the prediction of Hypothesis 3, the focal firm's *Internal Usage* of the abandoned patent has a significant positive moderating effect ($\beta_{CI} = 0.091, p_{CI} < 0.1$). Thus, Hypothesis 3 is supported.

Model 5 incorporates the interaction term of *Quality* of the knowledge spillover pool and the focal firm's *Open Innovation*. Hypothesis 4 predicts that focal firm's prior reliance on external sources of inventions significantly positive moderate the positive relationship of the *Quality* of the knowledge spillover pool and focal firm's *Cumulative Inventions*. The interaction term is significantly positive in model 7 ($\beta_{CI} = 0.897, p_{CI} < 0.1$). Therefore, Hypothesis 4 is corroborated.

Model 6 incorporates the interaction term of *Quality* of the knowledge spillover pool and the focal firm's *Self-Owned Complementary Patents* to test Hypothesis 5. The interaction term is statistically insignificant. Thus, Hypothesis 5 is rejected.

Additional Analyses

First, I conduct two additional analyses to test the robustness of my empirical findings related to the effect of *Pool Quality*. I include the square term of *Pool Quality* into model 9 to test the potential diminishing or negative effect of *Pool Quality* on the focal firm's superior learning from the knowledge spillover pool. The coefficient of the square term is negative and statistically significant, which suggests an inverted U-shaped effect of *Pool Quality* on proportion of the focal firm's cumulative inventions building on the knowledge spillover pool. The empirical result suggests that although a higher quality knowledge-spillover pool provides the focal firm more opportunities of learning from such a spillover pool, the increasing complexity of a higher quality knowledge-spillover pool could also inhibit the focal firm's learning (Yang, Phelps, & Steensma, 2010). I also include the interaction term of *Pool Quality* and the *Number of External Inventors* within the knowledge spillover pool in Model 10 to examine a potential anti-commons problem. According to the anti-commons theory, the fragmentation of the intellectual property rights covered in the knowledge spillover pool would lead to an under-development of the inventions within the knowledge spillover pool (Ziedonis, 2004). The coefficient of the inter-action term is negative and statistically significant, which is consistent with the prediction of the anti-commons theory. This empirical result implies that while the focal firm abandons the patent to mitigate the first order anti-commons problem, it could also increase the costs of learning by creating a second order anti-commons problem. Therefore, the focal firm's superior capabilities in identifying and integrating inventions within the knowledge spillover pool are even more important for it to achieve positive value creation

and value capture from its patent abandonment strategy.[25]

Second, to test whether the focal firm's initial purpose of patent abandonment would influence its subsequent learning from the knowledge spillover pool, I divide my full sample into two sub-samples and conduct similar empirical estimation separately. In Sample 1, I include the cases in which the focal firm abandons the patent, but at the same time renews at least one related patent, which is subject to renew and abandon. In Sample 2, I include the cases in which the focal firm abandons the patent, as well as all the other related patents that are subject to renew and abandon. Although not ideal, the way of separating the full sample can partially reflect the focal firm's initial purpose for patent abandonment. In Sample 1, the focal firm is more likely to abandon the patent for knowledge searching and subsequent learning. However, in Sample 2, the focal firm's patent abandonment is more likely to reflect its decision to abandon a certain line of research, which is consistent with the conventional wisdom in existing literature. The empirical results based on Sample 1, which are shown in Table 3.7(1), are consistent with the empirical results based on the full sample. However, the results based on Sample 2, which are shown in Table 3.7(2), are very different from the empirical results based on the full sample. The results suggest that the focal firm cannot efficiently learn from the knowledge spillover pool when it abandons all the related patents at the same time. In addition, the results provide some evidence that the focal firm can better benefit from its patent abandonment through subsequent learning when it selectively abandons its patents.

[25] I also use the three-way interaction to see whether the moderators in Chapter 3 would help reduce the second order anti-commons problem. The results, shown in Table 3.6 (2), show that the exploitative search path in initial invention creation stage and prior external knowledge sourcing would enable the focal firm to overcome second order anti-commons problem, while the internal usage and the self-owned complementary patents would not reduce the second order anti-commons problem.

Third, while the focal firm citing the knowledge spillover pool is suggestive of a plausible learning mechanism, the focal firm's learning from the knowledge spillover pool can be more strongly corroborated when the focal firm cites its originally abandoned patent in addition to citing patents contained in the knowledge spillover pool. Thus, I create a dependent variable based on the cases in which the focal firm cites its own original abandoned patent along with citing patents within the knowledge spillover pool (which consists of other firm's patents citing the focal firm's originally abandoned patent)[26]. The results in Table 3.8 are mostly similar with my main results in Table 3.5, which provide further evidence of focal firm's superior learning from a more valuable knowledge spillover pool created through its patent abandonment.

Fourth, I conduct further examinations of the role of complementary patents to analyze why the focal firm's learning from the knowledge spillover pool cannot be enhanced by holding more patents that are complementary. Two possible explanations are discussed here. First, the focal firm's holding more patents that are complementary enables it to appropriate more economic value when its patent abandonment strategy motivates broader external inventors to utilize the focal firm's abandoned patent. If the focal firm can capture substantial economic value through holding the complementary patents, the focal firm would have fewer incentives for subsequent learning. Second, when the focal firm's patent abandonment leads to more external inventors joining the knowledge-spillover pool, the focal firm might lose more from holding more patents that are complementary. For example, Toh and Miller (2017) maintain that the focal firm might face high expropriation

[26] In the full sample, there are only 6.24% such cases. In the case that the focal firm cites patents within the knowledge spillover pool, there are 20% of such cases. While such cases can be a strong reflection of the focal firm's learning from the knowledge spillover pool in developing its original patent, the focal firm has less incentive to cite its own original abandoned patent subsequently.

risk of disclosing its focal technology when holding complementary technologies. Khanna, Guler, and Nerkar (2018) show that owning interdependent innovations may enable the firm to appropriate higher returns from R&D investments ex-post (Arora, Fosfuri & Gambardella, 2001; Choi & Gerlach, 2017; Girotra, Terwiesch, & Ulrich, 2007; Teece, 1986). Removing inventions from the portfolio may then reduce the firm's ability to defend products from the competition.

To know which mechanism is more feasible, I conduct an additional analysis. I examine how the number of external inventors within the knowledge spillover pool would influence the usage of the focal firm's renewed complementary patents. I use negative binomial regression, in which the dependent variable is the forward citations of the focal firm's renewed complementary patents of each focal abandoned patent. The independent variable is the number of external inventors within the knowledge spillover pool created through the focal firm's abandoned patent. I also include firm-level and patent-level controls. Table 3.9 presents the empirical results, which show that as more inventors that are external join in the knowledge spillover pool for subsequent development of the focal firm's abandoned patents, the forward citations of the complementary patents owned by the focal firm increase. The empirical result provides partial support for the first explanation above that the focal firm's holding of more complementary patents enables it to appropriate more economic value.

3.4 Conclusion

The focal firm typically abandons its patents based on its internal resources and capabilities and the external market environment and technological development stage. However, technology is typically complex and cumulative, which makes it difficult to

measure precisely the exact economic value at a point in time. In addition, the focal firm, being bounded rationality, would likely undertake limited search in both exploration and exploitation of its technology when holding the patent. The focal firm's patent abandonment can motivate external inventors to work on the area of the abandoned patent, which can generate a substantially more economically valuable knowledge spillover pool than if the focal firm renewed this patent. Thus, it is possible that the focal firm's patent would realize more of its technological and market value through external inventors' subsequent development after the focal firm abandons its patent. The extant literature assumes that a patent cannot create economic value for the focal firm after it abandons the patent. Indeed, the research literature tends to emphasize that the focal firm would lose economic value when abandoning a patent, if this abandoned patent is later revealed by external inventors to have high market potential. In this chapter, I seek to contribute to the literature by submitting that the focal firm could also achieve positive value capture by learning from external inventors' development upon its originally abandoned patent. Because the focal firm often spends substantial resources in the initial discovery stage and subsequent development stage, it obtains familiarity with its own patent, which typically provides it with superior absorptive capacity for its subsequent learning from the knowledge spillover pool created through its patent abandonment. Therefore, the focal firm might benefit from its patent abandonment through subsequent learning from the knowledge spillover pool, which is enabled by its original patent abandonment.

This chapter explores the effects of the focal firm's patent abandonment on its superior capabilities in developing *cumulative inventions* that build on the patents within the knowledge spillover pool of the focal firm's abandoned patents. Such research has

several strategic implications. The extant research literature shows that the focal firm's abandoning poor patents can increase the economic value of the focal firm's overall patent portfolios (Lowe & Veloso, 2015). Low quality patents in the focal firm's patent portfolios would typically require that the focal firm spend substantial resources in order for the focal firm to maintain the economic value of its patents, which could delay negotiations of licensing agreements.[27] This chapter shows that the focal firm might also achieve positive value capture when it abandons patents that are later revealed to have high economic value. While the literature emphasizes that the focal firm abandon its patents that appear to be unpromising to reduce the unnecessary costs of patent maintenance and subsequent transactions, this chapter shows that the focal firm's abandoning some promising patents could enable the focal firm to identify more market opportunities for its abandoned patent, which could ultimately result in realizing more economic value of its patent.

The focal firm, instead of just viewing the subsequent unexpected usage of its abandoned patent by external inventors as negative consequences, can consider some positive perspectives of abandoning its patent. When a patent requires further development to be commercialized, and the focal firm lacks resources, knowledge, and/or capabilities for such further development, it can strategically abandon its patent to motivate broader external inventors with relevant resources, knowledge, and/or capabilities to develop the patent. The importance of such a strategic move is especially relevant if the traditional collaboration mode of licensing the technology does not comparatively work well due to a high level of exchange partner uncertainty, incentive misalignments, and coordination

[27] See http://www.iam-media.com/Intelligence/IAM-Yearbook/2016/Monetisation-and-strategy/Patent-portfolio-pruning-or-tuning-to-increase-IP-investment-returns

costs (Alexy, George & Salter, 2013). The external inventors might turn the initial economically non-viable patent into an economically valuable one through their further development. The focal firm, in turn, might achieve positive economic value capture if it can learn from these external inventors, and thus recombine the knowledge within the knowledge spillover pool with its own internal knowledge to create more valuable subsequent inventions. The extant literature has focused on that subsequent internal usage of the invention can generate new avenues for profiting from the original invention (Ahuja, Lampert & Novelli, 2013). The current chapter shows that the internal usage of the patent before the patent abandonment might also enable the focal firm profit from abandoning its patent. The focal firm's resources allocated in the development of the patent before its patent abandonment make it highly knowledgeable concerning this initial patent. Thus, when the focal firm abandons its initial patent it sets in motion a series of inventive responses by other firms, which due to the superior absorptive capacity of the focal firm can ultimately lead it to learn from the knowledge spillover pool of its abandoned patent.

Furthermore, the current chapter shows that the focal firm might not capture the economic value created through its patent abandonment by holding more patents that are complementary. On the one hand, the focal firm's ownership of complementary patents increases its bargaining power in its subsequent learning from the knowledge spillover pool, which can also attenuate the mutual economic holdup problem. On the other hand, however, the focal firm might also face high expropriation risk in disclosing its focal technology when holding complementary technologies. In particular, the external inventors might create a higher quality knowledge-spillover pool by utilizing a new set of complementary patents of the focal firm's abandoned patent. Under such circumstances,

the focal firm might lose the advantage in learning from the knowledge spillover pool through owning the original complementary patents of its abandoned patent. Therefore, the focal firm should be cautious in abandoning its patent, even though it has the ownership of a large amount of complementary assets.

As with many empirical studies, there are several limitations of the current chapter, which provides opportunities for future research. First, the current research discusses the impacts of the focal firm's abandoning patents with different characteristics on subsequent cumulative inventions. This chapter does not examine, however, whether the focal firm can obtain positive value capture through abandoning its patents. Future research is needed to provide a fuller comparative assessment of the focal firm's alternatives of abandoning or renewing its initial patent on its subsequent technology advancement and innovation performance. In addition, future research can evaluate whether and under what conditions the focal firm can earn positive economic rents through selectively abandoning its patent.

Second, I use patent citation data to track the focal firm's learning from the knowledge spillover pool, but such an operationalization has inherent limitations. On the one hand, considering the focal firm's learning from the knowledge spillover pool likely underestimates its learning gains because I do not take into account its learning in terms of non-patented inventions. On the other hand, the focal firm's filing of new patents citing the patent of the knowledge spillover pool does not necessarily solely represent a focal firm's learning and technology advancement. The focal firm can file the patent for defensive or strategic reasons, which over-estimates its learning gains from patent abandonment. Though I use a new measurement to deal with strategic patenting, it is by no means a perfect measure. Future research might develop a better measurement for cumulative invention to

get more detailed analysis of this issue (e.g., see Murray & O'Mahony (2007) for a review of cumulative innovation).

Third, this chapter does not distinguish whether the focal firm's original patent abandon-ment and subsequent learning is planned or emergent (Marcus, 2009; Mintzberg, 1978). Though in the additional analysis section, I try to divide the sample based on whether the focal firm renews any of the related patents when abandoning the focal patent, it is not a perfect way to reflect the initial purpose of patent abandonment. The empirical results provide some evidence that most of the focal firm's initial abandonment and subsequent learning might not be planned, and therefore the subsequent learning benefits cannot outweigh the negative spillover effects. However, if a focal firm strategically abandons its patents for idea generation in the first place, it might gain more benefits subsequently when the knowledge spillover pool is larger and broader. Future research -- perhaps through qualitative methods – can triangulate to examine how the focal firm's different motivations in patent abandonment can influence its subsequent inventions.

Finally, I only consider the focal firm's learning from the knowledge spillover pool in terms of the first generation development of its abandoned patent. However, the focal firm can learn from several generations of development of its initially abandoned patent (Belenzon, 2012). Future research can track multiple generations of the development of the focal firm's patent abandonment to achieve a more complete understanding of the benefits of this strategy. I hope that this research study proves fruitful in these and other ways for generating further theory refinements and econometric advances in our evolving strategy science.

Figures and Tables

Figure 3.1: Timeline of Invention Sequencing after the Focal Firm's Patent Abandonment

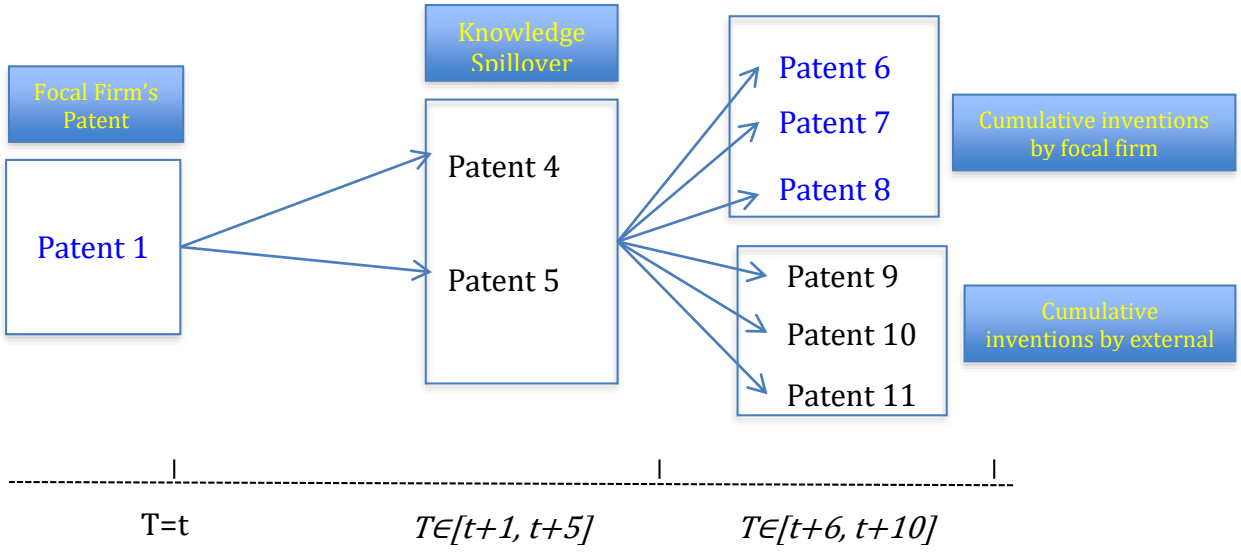


Figure 3.2: Hypothesis of Chapter 3

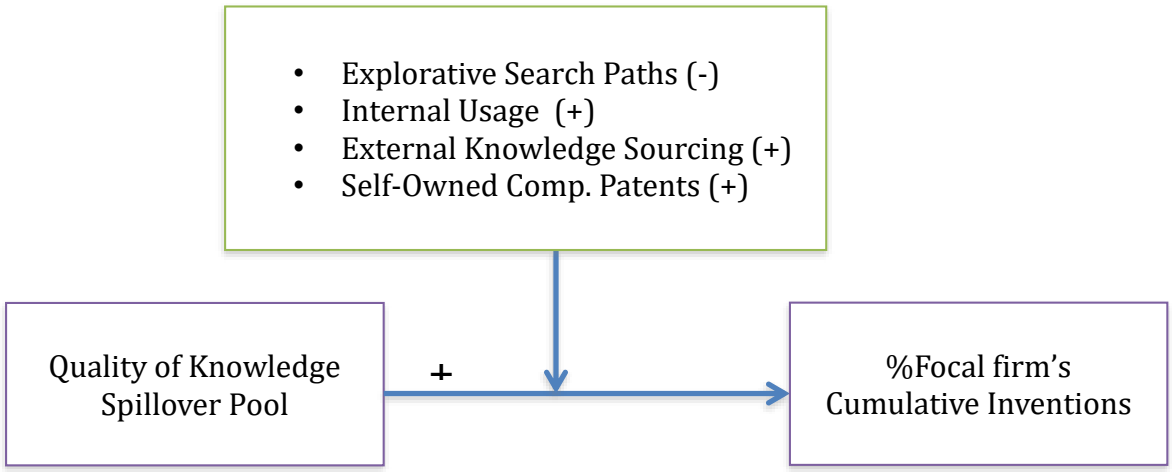


Table 3.1: Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Factors	Influence
Patent System	
Maintenance Cost	• Schankerman and Pakes (1985): If the maintenance cost increases, the optimal number of years of maintaining the patent will be shortened. • Baudry and Dumont (2006): The increase of the renewal fee will, on the one hand, decrease the patent option value of those "patent actually applied for," but on the other hand, increase the patent value through a screening process. The empirical results show that the latter positive impact on the patent value dominates. • Thomas (1999): After patent maintenance fees were doubled for patents applied for after August 1982, a larger proportion of patents is maintained at each renewal point, despite the increase in maintenance fees. • Lanjouw, Pakes, and Putnam (1998): The benefit to patentees of a decrease in renewal fee is twofold: they pay less for each year of protection, and, because it is less costly, they also tend to take advantage of more years of protection.
Application fee	• Baudry and Dumont (2006): Higher initial application fees can weed out patents with low quality.
Grant rate	• Schankerman (1998): The decline in grant rates reflects more stringent screening that weed out low-valued patents. Higher rates for a nationality, within a given technology field is associated with a higher mean value (provided patent screening does not depend on which country applies for the patent).
First-to-invent to first-to-file	• Moore (2005): If the rush to patent is substantial in the present first-to-invent system, it would likely be exacerbated if it changes to a first-to-file system.

Table 3.1 (cont.): Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Institutional or Economic factors	
Appropriability environment	• Cornelli and Schankerman (1996, 1999): From the government perspective, the higher the effectiveness of the appropriability environment should be negatively associated with the optimal patent length. From the firm perspective, the greater the appropriability, the longer the time that the firm will keep the patent. • Schankerman (1998): Institutional or economic factors such as the licensing policy, the stringency of price regulation, and the size of the relevant market will affect the patentee to appropriate the social surplus from their inventions.
Price Shock	• Schankerman (1998): A price shock will reduce the value of patent rights in all technology fields.
Patent characteristics	
Number of claims	• Barney (2002), Lowe and Veloso (2006), and Moore (2005): Patent maintenance rates increase with the number of claims.
Claim length	• Barney (2002): Patent maintenance rates generally decrease with claim length.
Length of written specification	• Barney (2002): Patent maintenance rates generally increase with the length of written specification.
Recorded priority claims to related cases	• Barney (2002): Patent maintenance rates generally increase with the number of recorded priority claims to related cases.
Forward citation rates	• Barney (2002) and Moore (2005): Forward citation rates are positively associated with patent maintenance rates. • Thomas (1999): Both self-citations and external citations are positively associated with patent renewal rates. • Serrano (2010): More frequently cited patents are more likely to be renewed. An extra citation decreases the predicted probability of a small innovator patent being allowed to expire at age 13 by about 1 percentage point as compared to the mean of the sample, which decreases from 36.9% to 35.9%.

Table 3.1 (cont.): Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Patent generality	• Serrano (2010): Patents with higher generality are more likely to be renewed.
Trade	• Serrano (2010): The probability of a previously traded patent expiring at any renewal date is lower than that of an untraded patent.
Inventors	• Moore (2005): Expired patents also listed fewer inventors than patents that were maintained. • Liu (2014): Having star inventors on the inventor team, the larger size of the inventor team, the cross-location collaboration of the invention team increases the likelihood that the patent will be renewed.
Ownership	• Lowe and Veloso (2006): There should be a lower renewal rate among patents for whose assignee is not located in U.S. • Moore (2005): Patents that are assigned to corporations are more likely to be maintained than those that are unassigned. • Moore (2005): Foreign companies are more likely to maintain the patent rights due to the high transaction cost rule out foreign companies to file low quality patents. • Thomas (1999): The proportion of assigned patents that go full term is far higher than the proportion of unassigned patents that do so.
Sequential innovations	• Liu, Arthurs, Cullen, and Alexander (2008): A patent that belongs to a sequence of patented innovations is more likely to be renewed.

Table 3.1 (cont.): Review of Factors that Influence the Focal Firm's Patent Renewal Decision

Age	• Serrano (2010): The probability of an active patent being allowed to expire increases with age.
Industry	• Pakes, Simpson, Judd, and Mansfield (1989): The order of the value of patent: pharmaceuticals and other chemical related industries > mechanical industries > electrical industries > low-tech industries. • Schankerman (1998): Pharmaceutical and chemical patents have relative low mean, high dispersion, and slow rate of depreciation. • Moore (2005): Results show that chemical, drugs, and medical industries are less likely to be maintained than mechanical; electrical & electronics; and communica-tions & computer patents, which contradicts the estimation of patent protection value. The explanation is that the pharmaceutical industry usually experiences a patent rush. • Thomas (1999): Patents in technological intense areas, such as data processing and biochemistry, often go full term. For example, electronics often go full term. A slightly lower proportion of pharmaceutical patent goes full term, which is caused by the high costs of clinical trials that are often undertaken before pharmaceutical patents become commercial products.
Firm	
Exploratory	• Lowe and Veloso (2006): Both "new to firm" and "new to science" patents are more likely to be abandoned by the focal firm.

Table 3.2: Literature of a Focal Firm's Learning from the Knowledge Spillover Pool

Paper	DV	IV/Measurement	Theoretical Prediction	Empirical Finding
Alnuaimi and George (2016)	Knowledge retrieval: whether spilled knowledge is retrieved	*Technological complexity*: A patent is defined as more complex if its components have not previously been integrated with a wide variety of other components	Inverted-U	Inverted-U
		Organizational coupling: Firm-level interdependencies between units of an organization, which occurs if inventors listed on a patent are from different regions	Inverted-U	Inverted-U
	Knowledge retrieval frequency: the number of times knowledge spillovers is used in a firm's subsequent patents.	*Technological complexity*: A patent is defined as more complex if its components have not previously integrated with a wide variety of other components	Inverted-U	Inverted-U
		Organizational coupling: Firm-level interdependencies between units of an organization, which occurs if inventors listed on a patent are from different regions	Inverted-U	Inverted-U
Yang, Phelps, and Steensma (2010)	Innovative output: the number of successful patent applications for firm *i* in year *t*.	*Pool size*: The total number of unique patents in firm i's spillover knowledge pool at year t-1	+	+
		Pool similarity: The distribution of a firm's patents across primary patent classes and the distribution of a firm's knowledge spillover pool across the primary class (Jaffe, 1986).	+	+
	Knowledge integration: the extent to which the innovative output of an originating firm built on the knowledge from its knowledge spillover pool as the proportion of prior art patents contained in firm i's patents of year t that belonged to its spillover knowledge pool in year t-1	Pool size: The total number of unique patents in firm i's spillover knowledge pool at year t-1	+	+
		Pool similarity: The distribution of a firm's patents across primary patent classes and the distribution of a firm's spillover knowledge pool across primary class (Jaffe, 1986).	+	+

Table 3.2 (cont.): Literature of a Focal Firm's Learning from the Knowledge Spillover Pool

Operti and Carnabuci (2014)	Firms' innovative performance: the number of patents granted to a firm, weighted by the number of forward citations each of these patents received within a 5-year interval	*Spillover network munificence*: The number of patented innovations each "source" firm generates during time t, weighted by the level of experience that the "recipient" firm has accumulated prior to time t about each source	+	+
		Structural holes: The extent to which a "recipient" firm i has directly or indirectly invested in accumulating experience about each of its "source" firm j.	+	+
		Scientific intensity (The extent to which a firm uses scientific knowledge to generate its technological innovation) * munificence	+	NS
		Scientific intensity (The extent to which a firm uses scientific knowledge to generate its technological innovation) * structural hole	+	+
		Downstream integration (Dummy variable that is coded 1 if an IDM or an original equipment manufacturer and 0 if it is a fabless firm) * munificence	-	-
		Downstream integration (Dummy variable that is coded 1 if an IDM or an original equipment manufacturer and 0 if it is a fabless firm) * structure hole	+	+
Yang and Steensma (2014)	Reliance on guided exploration: the extent to which an originating firm relied on its recipient firms for guidance in its subsequent exploration.	*Market growth*: Average growth rate in industry sales for year 1987 to year 1996 using a five-year moving window.	-	-
		Demand volatility: antilog of the standard errors of the quasi-time series regressions	+	+
		Market competitiveness: inverse of the top four companies' market share of firm i's primary four-digit SIC sector.	+	+

Table 3.2 (cont.): Literature of a Focal Firm's Learning from the Knowledge Spillover Pool

Phene and Tallman (2014)	Knowledge alliance formation: dummy variable, which equals 1 if (a) a strategic alliance if formed between firms involved in the spillover within five years of the date of the citing patent; and (b) the alliance was formed for purposes involving knowledge access, knowledge sharing, or collaborative research and development, and 0 otherwise.	*Specialization of originator in technological area of spillover*: the percentage of originating firms' patents in that technology class in the five years prior to the knowledge spillover	+	+
		Specialization of recipient in technological area of the spillover: the percentage of the recipient firms' patent in that technology class in the five years prior to the knowledge spillover.	-	-
		Technological ties between dyad members (the extent to which an originator and recipient have built on each other's knowledge) * Specialization of originator in technological area of the knowledge spillover	+	+
		Technological ties between dyad members (the extent to which an originator and recipient have built on each other's knowledge) * Specialization of recipient in technological area of the knowledge spillover	-	-
		Geographic distance between dyad members (geodesic distance scaled in hundreds of miles between the inventor locations of the originating and citing patent involved in the knowledge spillover) * Specialization of originator in technological area of the knowledge spillover	-	-
		Geographic distance between dyad members (geodesic distance scaled in hundreds of miles between the inventor locations of the originating and citing patent involved in the knowledge spillover) * Specialization of recipient in technological area of the knowledge spillover	+	+

Table 3.2 (cont.): Literature of a Focal Firm's Learning from the Knowledge Spillover Pool

Belenzon (2012)	Market value: sum of the value of common stock, preferred stock and total debt net of current assets.	*Share internal*: the ratio between the stock of internal citations (all citing patents on which the inventing firm builds on in a future period) and total citations stock.	+	+
		Share external: the ratio between the stock of external citations (patents that generate spillovers along research trajectories that are not exploited by the inventing firm) and total citations stock.	-	-

Table 3.3: Summary of Hypothesis 1 – Hypothesis 5

DV	IV	Theoretical Prediction	Empirical Finding
Citation weighted proportion of cumulative inventions that are belonged to the focal firm.	H1: Quality of Knowledge Spillover Pool	+	+
	H2: Quality of Knowledge Spillover Pool * Explorative Search Paths	-	-
	H3: Quality of Knowledge Spillover pool * Internal Usage	+	+
	H4: Number of External Inventors*External Knowledge Sourcing	+	+
	H5: Quality of Knowledge Spillover pool * Self-Owned Comp Patents	+	NS

Table 3.4: Summary Statistics and Correlation Matrix

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	%CI	1.00																	
2	Pool Quality	0.28	1.00																
3	# of External Inventors	-0.12	-0.07	1.00															
4	Explore	-0.11	-0.04	0.16	1.00														
5	Internal Usage	0.06	0.07	-0.13	-0.02	1.00													
6	Open Innovation	0.30	0.66	-0.04	-0.01	0.07	1.00												
7	Self-Owned Complement	0.06	0.15	-0.03	0.07	0.03	0.12	1.00											
8	Knowledge Similarity	0.15	-0.02	-0.18	-0.27	0.12	-0.03	-0.01	1.00										
9	Current Ratio	-0.15	-0.11	0.02	0.36	0.10	-0.07	0.00	-0.27	1.00									
10	R&D	-0.03	-0.06	0.08	0.50	0.01	-0.05	0.03	-0.43	0.57	1.00								
11	Firm Diversification	0.07	0.00	-0.09	-0.01	-0.01	-0.02	-0.02	0.12	-0.13	0.00	1.00							
12	Firm Size	0.19	0.04	-0.17	-0.46	0.10	0.02	-0.02	0.78	-0.52	-0.66	0.12	1.00						
13	# of Active Comp. Patents	0.07	0.03	-0.06	-0.23	0.09	-0.01	-0.06	0.03	-0.01	-0.12	-0.02	0.34	1.00					
14	Patent Scope	0.27	0.28	-0.17	-0.15	0.11	0.20	0.04	0.24	-0.14	-0.10	0.07	0.25	0.09	1.00				
15	Prior Forward Citations	0.14	0.27	-0.26	-0.12	0.22	0.17	0.16	0.17	-0.01	-0.09	-0.03	0.19	0.10	0.33	1.00			
16	Backward Citations	0.01	-0.03	0.03	0.03	-0.07	0.03	-0.02	-0.02	0.07	0.05	0.02	-0.06	-0.06	-0.03	-0.06	1.00		
17	Abandon Stage_2nd	0.10	0.08	-0.06	-0.07	0.01	0.05	-0.00	0.18	-0.17	-0.12	0.09	0.28	0.10	0.15	0.02	-0.01	1	
18	Abandon Stage_3rd	0.16	0.55	-0.09	0.03	0.18	0.47	0.22	0.02	-0.05	0.00	-0.03	0.03	0.07	0.46	0.43	-0.03	0.03	1
	Mean	0.01	0.81	3.77	0.85	0.03	6.77	0.06	0.34	1.54	80.10	0.12	0.19	67.77	1.23	7.54	5.93	0.44	0.18
	S.D.	0.06	1.34	3.06	0.06	0.05	10.60	0.09	0.30	0.49	137.55	0.05	0.16	83.62	0.63	7.93	4.56	0.50	0.38
	Min	0	0.01	1	0.43	0	1	0	0	0.60	7.15	0.06	0.00	1	1	0	1	0	0
	Max	0.80	10.95	25	1	0.435	112	1	1	5.53	1462.5	0.50	0.76	824	4	89	56	1	1

Table 3.5: Regression Results

	(1)	(2)	(3)	(4)	(5)	(6)
Independent Variables						
Pool Quality		**0.096*** **	**0.160** **	**0.141** **	**-0.697**	**0.151*** **
		(0.035)	**(0.054)**	**(0.057)**	**(0.004)**	**(0.051)**
Moderators						
Exploration	0.005	0.005	0.015***	0.007	0.006	0.007
	(0.005)	(0.005)	(0.006)	(0.005)	(0.005)	(0.005)
Internal Usage	-0.005	-0.005	-0.001	-0.006	-0.001	-0.001
	(0.007)	(0.007)	(0.007)	(0.009)	(0.007)	(0.007)
Open Innovation	-0.019	0.034	-0.023	-0.032	-0.074	-0.026
	(0.047)	(0.039)	(0.042)	(0.043)	(0.055)	(0.041)
Self-Owned Complement	0.059	0.072*	0.087**	0.087**	0.092**	0.077
	(0.041)	(0.042)	(0.042)	(0.042)	(0.042)	(0.051)
Pool Quality			-0.109**			
* Exploration			(0.048)			
Pool Quality				0.091*		
* Internal Usage				(0.057)		
Pool Quality					0.897*	
* Open Innovation					(0.496)	
Pool Quality						0.089
* Self-Owned Complement						(0.042)
Control Variables						
# of External Inventors	0.001	0.001	0.002**	0.003**	0.003**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Knowledge Similarity	-0.004**	-0.004**	-0.005***	-0.005***	-0.004**	-0.005**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Current Ratio	0.022**	0.013*	0.017**	0.017**	0.017**	-0.018**
	(0.009)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
R&D	0.000	0.000	0.000	0.000*	0.000	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm diversification	-0.033	-0.046	-0.014	-0.017	-0.016	-0.013
	(0.030)	(0.030)	(0.028)	(0.028)	(0.028)	(0.028)
Firm Size	-0.000	0.000*	0.241***	0.239***	0.239***	0.240***
	(0.000)	(0.000)	(0.039)	(0.039)	(0.039)	(0.039)
# Patent Application	-0.000**	-0.000***	-0.000**	-0.000**	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# Patent Abandonment	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# of Active Complement	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Patent Scope	0.001	0.003	0.003	0.002	0.003	0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Prior forward citations	-0.000	-0.000	-0.001	-0.001	-0.001	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Backward Citations	0.001	0.002**	0.002**	0.002**	0.002**	0.002**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Abandon Stage_2nd Stage	-0.002	-0.013	-0.014	-0.014	-0.014	-0.013
	(0.010)	(0.011)	(0.010)	(0.010)	(0.010)	(0.010)
Abandon Stage_3rd Stage	-0.010	-0.036**	-0.036**	-0.036**	-0.035**	-0.034**
	(0.013)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
Constant	-0.003	-0.038	-0.015	0.002	0.036	0.008
	(0.046)	(0.043)	(0.043)	(0.045)	(0.054)	(0.043)
Firm Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.146	0.148	0.153	0.152	0.168	0.152
N	1008	1008	1008	1008	1008	1008

Note:

1. * p<0.1; ** p<0.05; *** p<0.01
2. Robustness Standard Errors are in parentheses.

Table 3.6 (1): Additional Analysis I

	(7)	(8)	(9)	(10)
Independent Variables				
Pool Quality		0.096***	**0.147****	**0.196*****
		(0.035)	**(0.067)**	**(0.066)**
Pool Quality ^2			**-0.138****	**-0.043**
			(0.075)	**(0.098)**
Pool Quality * # External Inventors				**-0.008****
				(0.000)
Moderators				
Exploration	-0.005	0.005	0.006	0.007
	(0.005)	(0.005)	(0.005)	(0.005)
Internal Usage	-0.005	-0.005	-0.005	-0.001
	(0.007)	(0.007)	(0.007)	(0.007)
Open Innovation	-0.019	0.034	-0.017	-0.028**
	(0.047)	(0.039)	(0.047)	(0.042)
Self-Owned Complement	0.059	0.072*	0.058	0.089**
	(0.041)	(0.042)	(0.041)	(0.042)
Control Variables				
# External Inventors	0.001	0.001	0.000	0.002
	(0.001)	(0.001)	(0.001)	(0.002)
Knowledge Similarity	-0.004**	-0.004**	-0.005**	-0.005**
	(0.002)	(0.002)	(0.002)	(0.002)
Current Ratio	0.022**	0.013*	0.018**	0.018**
	(0.009)	(0.007)	(0.007)	(0.008)
R&D	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Firm diversification	-0.033	-0.046	-0.012	-0.014
	(0.030)	(0.030)	(0.028)	(0.028)
Firm Size	-0.000	0.000*	0.242***	0.242***
	(0.000)	(0.000)	(0.039)	(0.039)
# Patent Application	-0.000**	-0.000***	-0.000**	-0.000***
	(0.000)	(0.000)	(0.000)	(0.000)
# Patent Abandonment	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)
# of Active Complement	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Patent Scope	0.001	0.003	0.003	0.003
	(0.003)	(0.003)	(0.003)	(0.003)
Prior forward citations	-0.000	-0.000	-0.000	-0.001
	(0.000)	(0.000)	(0.011)	(0.000)
Backward Citations	0.001	0.002**	0.002**	0.002**
	(0.001)	(0.001)	(0.001)	(0.001)
Abandon Stage_2nd Stage	-0.002	-0.013	-0.014	-0.014
	(0.010)	(0.011)	(0.010)	(0.010)
Abandon Stage_3rd Stage	-0.010	-0.036**	-0.036**	-0.035**
	(0.013)	(0.016)	(0.016)	(0.016)
Constant	-0.003	-0.038	-0.003	-0.006
	(0.046)	(0.043)	(0.043)	(0.043)
Firm Dummies	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes
R^2	0.146	0.148	0.150	0.151
N	1008	1008	1030	1030

Note:

2. * p<0.1; ** p<0.05; *** p<0.01

3. Robustness Standard Errors are in parentheses.

Table 3.6 (2): Additional Analysis I: Moderators and second order anti-commons problem

	(11)	(12)	(13)	(14)	(15)
Independent Variables					
Pool Quality	0.183***	0.190***	0.192**	0.164***	0.192***
	(0.053)	(0.054)	(0.057)	(0.060)	(0.054)
Pool Quality	-0.010**	-0.007*	-0.016**	-0.060*	-0.013**
* # of External Inventors	(0.004)	(0.004)	(0.007)	(0.033)	(0.015)
Moderators					
Exploration	0.006	0.009*	0.006	0.006	0.007
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Internal Usage	-0.004	-0.004	-0.006	-0.004	-0.001
	(0.007)	(0.007)	(0.008)	(0.007)	(0.007)
Open Innovation	0.035	0.038	0.036	0.016	0.039
	(0.039)	(0.038)	(0.038)	(0.043)	(0.038)
Self-Owned Complement	0.073*	0.072*	0.087**	0.075*	0.065
	(0.042)	(0.042)	(0.042)	(0.042)	(0.045)
Pool Quality* # of External		-0.005*			
Inventors * Exploration		(0.03)			
Pool Quality * # of External			0.006		
Inventors * Internal Usage			(0.005)		
Pool Quality * # of External				0.059*	
Inventors * Open Innovation				(0.040)	
Pool Quality* # of External					0.037
Inventors* Self-Owned Complement					(0.031)
Control Variables					
# of External Inventors	0.002*	0.002**	0.003**	0.003**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Knowledge Similarity	-0.005**	-0.005***	-0.005***	-0.004**	-0.005**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Current Ratio	0.013*	0.017**	0.017**	0.017**	-0.018**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
R&D	0.000	0.000	0.000*	0.000	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm diversification	-0.046	-0.014	-0.017	-0.016	-0.013
	(0.030)	(0.028)	(0.028)	(0.028)	(0.028)
Firm Size	0.000*	0.241***	0.239***	0.239***	0.240***
	(0.000)	(0.039)	(0.039)	(0.039)	(0.039)
# Patent Application	-0.000***	-0.000**	-0.000**	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# Patent Abandonment	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# of Active Complement	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Patent Scope	0.003	0.003	0.002	0.003	0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Prior forward citations	-0.000	-0.001	-0.001	-0.001	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Backward Citations	0.002**	0.002**	0.002**	0.002**	0.002**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Abandon Stage_2nd Stage	-0.013	-0.014	-0.014	-0.014	-0.013
	(0.011)	(0.010)	(0.010)	(0.010)	(0.010)
Abandon Stage_3rd Stage	-0.036**	-0.036**	-0.036**	-0.035**	-0.034**
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
Constant	-0.038	-0.015	0.002	0.036	0.008
	(0.043)	(0.043)	(0.045)	(0.054)	(0.043)
Firm Dummies	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes
R^2	0.151	0.152	0.155	0.152	0.152
N	1008	1008	1008	1008	1008

Note:

1. * p<0.1; ** p<0.05; *** p<0.01
2. Robustness Standard Errors are in parentheses.

Table 3.7 (1): Additional Analysis II: Sample 1 renew at least one related patent

	(11)	(12)	(13)	(14)	(15)
Independent Variables					
Pool Quality	0.097***	0.157**	0.141**	-0.670	0.152***
	(0.035)	(0.054)	(0.057)	(0.480)	(0.055)
Moderators					
Exploration	0.005	0.015***	0.007	0.006	0.007
	(0.005)	(0.006)	(0.005)	(0.005)	(0.005)
Internal Usage	-0.005	-0.001	-0.006	-0.001	-0.001
	(0.007)	(0.007)	(0.009)	(0.007)	(0.007)
Open Innovation	0.034	-0.023	-0.032	-0.074	-0.026
	(0.039)	(0.042)	(0.043)	(0.055)	(0.041)
Self-Owned Complement	0.072*	0.087**	0.087**	0.092**	0.077
	(0.042)	(0.042)	(0.042)	(0.042)	(0.051)
Pool Quality		-0.112**			
* Exploration		(0.048)			
Pool Quality			0.085*		
* Internal Usage			(0.062)		
Pool Quality				0.867*	
* Open Innovation				(0.524)	
Pool Quality					0.426
* Self-Owned Complement					(0.352)
Control Variables					
# of External Inventors	0.001	0.002**	0.003**	0.003**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Knowledge Similarity	-0.004**	-0.005***	-0.005***	-0.004**	-0.005**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Current Ratio	0.013*	0.017**	0.017**	0.017**	-0.018**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
R&D	0.000	0.000	0.000*	0.000	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm diversification	-0.046	-0.014	-0.017	-0.016	-0.013
	(0.030)	(0.028)	(0.028)	(0.028)	(0.028)
Firm Size	0.000*	0.241***	0.239***	0.239***	0.240***
	(0.000)	(0.039)	(0.039)	(0.039)	(0.039)
# Patent Application	-0.000***	-0.000**	-0.000**	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# Patent Abandonment	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# of Active Complement	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Patent Scope	0.003	0.003	0.002	0.003	0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Prior forward citations	-0.000	-0.001	-0.001	-0.001	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Backward Citations	0.002**	0.002**	0.002**	0.002**	0.002**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Abandon Stage_2nd Stage	-0.013	-0.014	-0.014	-0.014	-0.013
	(0.011)	(0.010)	(0.010)	(0.010)	(0.010)
Abandon Stage_3rd Stage	-0.036**	-0.036**	-0.036**	-0.035**	-0.034**
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
Constant	-0.038	-0.015	0.002	0.036	0.008
	(0.043)	(0.043)	(0.045)	(0.054)	(0.043)
Firm Dummies	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes
R^2	0.152	0.156	0.155	0.152	0.155
N	468	468	468	468	468

Note:

1. * p<0.1; ** p<0.05; *** p<0.01
2. Robustness Standard Errors are in parentheses.

Table 3.7 (2): Additional Analysis II: Sample 2 abandon all related patent

	(16)	(17)	(18)	(19)	(20)
Independent Variables					
Pool Quality	0.128	0.134	0.084	3.164*	0.059
	(0.158)	(0.161)	(0.165)	(1.886)	(0.153)
Moderators					
Exploration	0.005	0.015***	0.007	0.006	0.007
	(0.005)	(0.006)	(0.005)	(0.005)	(0.005)
Internal Usage	-0.005	-0.001	-0.006	-0.001	-0.001
	(0.007)	(0.007)	(0.009)	(0.007)	(0.007)
Open Innovation	0.034	-0.023	-0.032	-0.074	-0.026
	(0.039)	(0.042)	(0.043)	(0.055)	(0.041)
Self-Owned Complement	0.072*	0.087**	0.087**	0.092**	0.077
	(0.042)	(0.042)	(0.042)	(0.042)	(0.051)
Pool Quality		0.148			
* Exploration		(0.128)			
Pool Quality			0.199		
* Internal Usage			(0.158)		
Pool Quality				-3.262	
* Open Innovation				(1.963)	
Pool Quality					2.872*
* Self-Owned Complement					(1.638)
Control Variables					
# of External Inventors	0.001	0.002**	0.003**	0.003**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Knowledge Similarity	-0.004**	-0.005***	-0.005***	-0.004**	-0.005**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Current Ratio	0.013*	0.017**	0.017**	0.017**	-0.018**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
R&D	0.000	0.000	0.000*	0.000	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm diversification	-0.046	-0.014	-0.017	-0.016	-0.013
	(0.030)	(0.028)	(0.028)	(0.028)	(0.028)
Firm Size	0.000*	0.241***	0.239***	0.239***	0.240***
	(0.000)	(0.039)	(0.039)	(0.039)	(0.039)
# Patent Application	-0.000***	-0.000**	-0.000**	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# Patent Abandonment	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# of Active Complement	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Patent Scope	0.003	0.003	0.002	0.003	0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Prior forward citations	-0.000	-0.001	-0.001	-0.001	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Backward Citations	0.002**	0.002**	0.002**	0.002**	0.002**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Abandon Stage_2nd Stage	-0.013	-0.014	-0.014	-0.014	-0.013
	(0.011)	(0.010)	(0.010)	(0.010)	(0.010)
Abandon Stage_3rd Stage	-0.036**	-0.036**	-0.036**	-0.035**	-0.034**
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
Constant	-0.038	-0.015	0.002	0.036	0.008
	(0.043)	(0.043)	(0.045)	(0.054)	(0.043)
Firm Dummies	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes
R^2	0.388	0.393	0.406	0.409	0.420
N	101	101	101	101	101

Note:

1. * p<0.1; ** p<0.05; *** p<0.01
2. Robustness Standard Errors are in parentheses.

Table 3.8: Additional Analysis III Dependent variable based on the cases in which the focal firm cites the original patent along with patents within the knowledge spillover pool

	(21)	(22)	(23)	(24)	(25)	(26)
Independent Variables						
Pool Quality		**0.047**	**0.544****	**0.105**	**-0.744**	**0.140***
		(0.108)	**(0.258)**	**(0.114)**	**(0.795)**	**(0.093)**
Moderators						
Exploration	0.004	0.004	0.032**	0.008	0.003	0.012
	(0.011)	(0.011)	(0.015)	(0.011)	(0.011)	(0.011)
Internal Usage	0.006	0.006	0.008	-0.012	0.006	0.004
	(0.013)	(0.013)	(0.013)	(0.014)	(0.013)	(0.012)
Open Innovation	-0.284***	-0.283***	-0.267***	-0.279***	-0.330***	-0.251***
	(0.079)	(0.079)	(0.077)	(0.077)	(0.097)	(0.074)
Self-Owned Complement	0.031	0.031	0.028	0.027	0.034	-0.047
	(0.077)	(0.077)	(0.077)	(0.077)	(0.078)	(0.096)
Pool Quality			-0.318*			
* Exploration			(0.193)			
Pool Quality				0.402***		
* Internal Usage				(0.150)		
Pool Quality					0.895	
* Open Innovation					(0.904)	
Pool Quality						2.312*
* Self-Owned Complement						(1.244)
Control Variables						
# of External Inventors	-0.002	-0.002	0.001	0.002	-0.002	0.000
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Knowledge Similarity	-0.003	-0.004	-0.007*	-0.006*	-0.004	-0.005
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Current Ratio	0.094***	0.093***	0.090***	0.088***	0.093***	0.089***
	(0.023)	(0.022)	(0.022)	(0.022)	(0.022)	(0.022)
R&D	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm diversification	-0.033	0.079	0.071	0.057	0.077	0.076
	(0.030)	(0.055)	(0.053)	(0.052)	(0.055)	(0.052)
Firm Size	0.080	0.000	0.000	0.000	0.000	0.000
	(0.055)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# Patent Application	-0.000**	-0.000***	-0.000**	-0.000**	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# Patent Abandonment	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
# of Active Complement	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Patent Scope	-0.014***	-0.014***	-0.015***	-0.016***	-0.014***	-0.015***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Prior forward citations	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Backward Citations	-0.002***	-0.002***	-0.002***	-0.002***	-0.002***	-0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Abandon Stage_2nd Stage	-0.048**	-0.047**	-0.046**	-0.044**	-0.047**	-0.041**
	(0.020)	(0.018)	(0.018)	(0.018)	(0.019)	(0.017)
Abandon Stage_3rd Stage	-0.030	-0.028	-0.028	-0.028	-0.029	-0.020
	(0.023)	(0.022)	(0.022)	(0.022)	(0.022)	(0.021)
Constant	0.191***	0.189***	0.150**	0.196***	0.232***	0.151**
	(0.072)	(0.070)	(0.068)	(0.070)	(0.089)	(0.067)
Firm Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.16	0.16	0.17	0.18	0.16	0.18
N	1008	1008	1008	1008	1008	1008

Table 3.9: Additional Analysis IV: Forward citations of active complementary patents after the focal firm's patent abandonment

	DV=Forward Citations		
	(27)	(28)	(29)
Pool Quality	**0.336*** **		**0.376*** **
	(0.036)		**(0.048)**
# of External Inventors		**1.660*** **	**-0.468***
		(0.221)	**(0.287)**
<u>Pool-level control</u>			
Knowledge Similarity	-11.582*	-10.189**	-11.391*
	(6.128)	(6.163)	(6.131)
<u>Firm-level control</u>			
Current Ratio	0.139	-0.594	0.023
	(1.131)	(1.163)	(1.140)
R&D	0.006	0.016**	0.005
	(0.007)	(0.007)	(0.007)
Firm Size	-0.001	-0.004	-0.001
	(0.007)	(0.007)	(0.007)
Firm Diversification	9.063	5.597	9.950**
	(8.011)	(8.389)	(8.029)
Open Innovation	2.096	2.534	2.277
	(10.993)	(11.193)	(10.951)
<u>Patent-level control</u>			
Exploration	0.636***	-0.733***	-0.650***
	(0.198)	(0.204)	(0.197)
Internal Usage	-0.337***	-0.361***	-0.249**
	(0.117)	(0.123)	(0.122)
Patent Scope	-0.381	-0.318	-0.416
	(0.463)	(0.476)	(0.463)
Prior Forward Citation	0.965***	0.973***	0.966***
	(0.035)	(0.035)	(0.035)
Backward Citations	0.250***	0.307***	0.247***
	(0.069)	(0.067)	(0.070)
Abandon Stage _2nd Stage	-1.127	-1.121	-1.127
	(1.421)	(1.457)	(1.421)
Abandon Stage _ 3rd Stage	-4.675***	-5.030***	-4.675***
	(1.362)	(1.377)	(1.362)
Firm Dummies	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes

Note:

1. * $p<0.1$; ** $p<0.05$; *** $p<0.01$
2. Robustness Standard Errors are in parentheses.

CHAPTER 4: THE FOCAL FIRM'S PATENT ABANDONMENT AND SEARCH FOR SUBSEQUENT INVENTIONS: DISTANT KNOWLEDGE, NEW-TO-FIRM INVENTORS AND TECHNOLOGICAL STRENGTH

4.1 Introduction

Innovation is typically cumulative, which means the focal firm's patents might not create sufficient economic value to the society, as well as to the focal firm if the focal firm fails to explore its patents full potential through subsequent developments. Further, modern technologies are typically dynamic and often overlap multiple fields and application areas. Thus, to realize more economic value of its patent, the focal firm should explore more usability of its patents in areas that it might not be familiar with in practice. Though the focal firm can use multiple strategies to search by itself (Gavetti & Levinthal, 2000; Gavetti, Levinthal, & Rivkin, 2005), it is almost impossible to explore the full potential of all inventions without opening up the invention development process. This dissertation has emphasized that the focal firm's patent abandonment can enable external inventors' collective search for exploiting and exploring more services/ applications of its patent. Further, by relying on external inventors' collective search, the focal firm can identify distant knowledge and potentially new inventors, which facilitate its future inventions.

Once the U.S. Patent and Trademark Office (USPTO) issues the patent, the patent holder is required to pay the USPTO three maintenance fees to keep the patent in force, which are due at the end of the 4^{th}, 8^{th} and 12^{th} years after the patent is granted. The patent is abandoned by the patent holder and consequently becomes freely available for the public to use if the patent holder declines paying any of the maintenance fees and/or surcharge at the end of 4^{th}, 8^{th}, and 12^{th}years of issuance. Based on Chapter 2, whether planned or unplanned by the focal firm's decision makers, the focal firm's patent abandonment can

motivate external inventors with relevant knowledge to conduct more and broader subsequent inventions that build on the focal firm's abandoned patent. Thus, the patent, though abandoned by the focal firm, is more likely to realize more market and technological value through external inventors' collective search in subsequent developments. In Chapter 3, I show that the focal firm can develop subsequent inventions that build on patents within the knowledge spillover pool through learning from the external inventors' subsequent development of its abandoned patent. In this chapter, I combine the extant research literature of search for innovation and organizational learning to explore how the focal firm can use patent abandonment strategy to overcome its own search limitation. In particular, my primary research question examines which inventions within the knowledge spillover pool, created by external inventors through the focal firm's patent abandonment, are more likely to be integrated by the focal firm in its subsequent innovation.

This chapter relaxes the neoclassical economics assumption in the patent renewal and abandonment literature and proposes that the focal firm's patent abandonment decision is not always a dichotomous choice between terminating and continuing a line of research projects. Sometimes, the patent abandonment decision is about a transformation of search strategy for the subsequent development of the focal firm's underdeveloped inventions. The developed theory in this chapter is that the focal firm's patent abandon-ment could open up its innovation process to the public, which can transform its own limited search into broader external inventors' collective search. The external inventors with relevant knowledge would be motivated to develop further the focal firm's abandoned patent. The focal firm can rely on external inventors' collective search and integrate valuable

inventions within the knowledge spillover pool that are created through external inventors' collective search into its subsequent inventions. In this chapter, I submit that the focal firm's patent abandonment can complement the focal firm's existing search strategy and enable the focal firm to identify distant knowledge and new hidden partners, which can facilitate the focal firm's future inventions. This chapter also examines the limitations of the focal firm's reliance on external inventors' collective search. Though the focal firm can abandon its patent to motivate external inventors' collective search to access distant knowledge and new partner, it is more likely to integrate the inventions that are in its familiar area due to its superior absorptive capacity and knowledge familiarity.

This chapter applies patent abandonment data and patent data of semiconductor industry to test empirically how the focal firm could use patent abandonment strategy to search for future innovation. The empirical results first show that the focal firm is more likely to integrate the patents within the knowledge spillover pool that are recombined with more distant knowledge into its future innovation. Second, the focal firm is more likely to use the patents that are created by new external inventors in its future inventions. Third, the focal firm is more likely to integrate the patents within the knowledge spillover pool that belong to the focal firm's familiar technological area. All of these empirical results corroborate my theory-driven hypotheses.

This chapter contributes to the emerging literature on innovation search and organization learning. First, it highlights that the focal firm can rely on a patent abandonment strategy to search for distant knowledge and new partners, which enables the focal firm to create and capture value. Second, it shows that the focal firm's existing knowledge base is critical to the focal firm's search strategy from the knowledge- spillover

pool created through its patent abandonment. The chapter shows that though the focal firm might integrate inventions that are recombined with distant knowledge and created by unfamiliar external inventors, the focal firm is still more likely to integrate the inventions that are in its familiar domain due to its superior absorptive capacity.

4.2 Theory and Hypotheses

Currently, innovation is becoming more cumulative and open, which requires the collaboration of multiple inventors. The focal firm's inventions typically require several subsequent developments to realize their full economic value. Furthermore, modern technologies are dynamic and often overlap multiple fields and application areas.[28] For example, virtual reality -- a branch of computer technology -- has applications in several major industries including the military, health care, and entertainment industries. Thus, to realize more economic value of its invention, the focal firm should look beyond its actual competition and explore more usability of its invention in areas that it might not be familiar with in practice. The knowledge recombination view of innovation suggests that the focal firm's capabilities in recombining knowledge both within its domain and across domains are critical to its innovation performance (Fleming, 2001; Laursen, 2012). The focal firm needs to search both internally and externally to broaden and deepen its knowledge base (Yayavaram, Srivastava, & Sarkar, 2018). The focal firm can either conduct its own boundary-spanning search (Laursen, 2012) or, as the current research has emphasized, abandon its patent to enable collective search by external inventors for exploring more services/ applications of its patent.

[28] See https://www.greyb.com/patent-portfolio-strategy-filing-patent-continuations/

This chapter proposes that the focal firm's patent abandonment can transform its limited internal search into external inventors' collective search, which facilitates further development of the focal firm's underdeveloped invention. The transformation of search strategy might enable the focal firm to identify more commercial usability of its invention and hidden knowledge in subsequent developing its inventions.

There are several reasons external inventors' inventions that build on the focal firm's abandoned patent could be more economically valuable to the focal firm if their inventions are recombined with knowledge that is more distant from the focal firm's existing knowledge base. First, when the focal firm's abandoned patent is recombined with distant knowledge, it might create more market and technological value to the focal firm's abandoned patent, which is under-discovered by the focal firm before it abandons the patent. In many cases, firms had expended considerable internal unsuccessful effort in searching for development of the invention. Therefore, the selection process might be biased toward "out-of-field" subsequent development, which typically appears to be quite different from internal attempts (Jeppesen and Lakhani, 2010; Nerkar & MacMillan, 2003). The current research considers both emergent and planned strategy. It is possible that when the focal firm abandoned its patent, it perceives the economic value of the patent is less than the cost of maintaining the patent after search for exploration and exploitation of the patent internally. However, external inventors might explore some unexpected usage of the original abandoned patent and create subsequent cumulative inventions, which transforms the initial un-valuable patent into a valuable one. I submit that the more distant knowledge that is used by external inventors in subsequent development, the greater the economic value that might be created to the abandoned patent and the higher the possibilities that the

focal firm can identify useful knowledge for subsequent innovation. When the focal firm holds a patent that provides exclusive rights over the use of its technology, it can either develop its invention through internal search for knowledge or rely on designated partners through traditional modes of collaboration[29] (Afuah & Tucci, 2012; Alexy, George, & Salter, 2013). With either mechanism, its search in exploration and exploitation of the patent is posited to be bounded, in the sense that it is more likely to restrict its attention within its familiar area (Cyert & March, 1963; Ocasio, 1997) and conduct intelligent searches where its routines, cognitive framing, and absorptive capacity enables its effective assessment of alternatives and consequences (Afuah & Tucci, 2012; Cohen & Levinthal, 1990). The focal firm, while searching for subsequent development of its patent, might ignore the knowledge that is distant from the focal firm's existing knowledge base. Thus, when the external inventors later develop the patent through recombining knowledge that is distant from the focal firm's existing knowledge base, it might explore more market and technological value of its patent, which is less explored by the focal firm before it abandons the patent.

Second, not only can distant knowledge add more market and technological potential to the abandoned patent, but it can also create more economic value to the focal firm. The larger the distance between the focal firm's knowledge base and the knowledge required to develop further its invention, the more difficult it may be for the focal firm to locate, evaluate, transfer, and recombine the knowledge needed to subsequent develop the initial invention. In such a situation, external inventors' collective search may be a better

[29] The focal firm can also open up the intellectual property rights without abandon the patents, such as patent pledge (e.g. http://www.pijip.org/non-sdo-patent-commitments/). The phenomenon is not very common so far, so it is not the focus of the current chapter. However, the investigation of such hybrid mechanisms can be useful.

mechanism for subsequent development of the invention than internal search or designated contracting. An increase in the distance between the focal firm's knowledge base and the required knowledge for subsequent development of the invention makes external inventors' collective search more valuable because as the distance increases, it becomes increasingly difficult for the focal firm to rely merely on internal search for subsequent development of its invention. When the focal firm holds the patent to have exclusive rights over the use of its technology, it can either develop its invention through internal search of knowledge or rely on designated partners through traditional modes of collaboration[30] (Afuah & Tucci, 2012; Alexy, George, & Salter, 2013). For the focal firm, the costs of conducting distant search are usually high, because it requires the focal firm to acquire new resources and capabilities, which lowers the focal firm's expected economic profitability (Afuah & Tucci, 2012). The focal firm can also collaborate with external inventors for knowledge exploitation and exploration through standard collaboration mechanisms (such as license or cross-license agreements). These collabora-tion mechanisms are usually under the shadow of contracts, which might create high transaction costs when involving distant knowledge recombination due to incomplete contracting problems. The extant literature shows that the focal firm can use broadcast search strategy to complement its existing search strategy to identify effectively and efficiently the distant knowledge (Alexy, George, & Salter, 2013; Jeppesen & Lakhani, 2010). The complexity of searching distant knowledge for recombination and the path dependence of the focal firm's search behavior make it difficult for the focal firm to develop the inventions internally (Yayavaram,

[30] The focal firm can also open up the intellectual property rights without abandon the patents, such as patent pledge (e.g. http://www.pijip.org/non-sdo-patent-commitments/). The phenomenon is not very common so far, so it is not the focus of the current chapter. However, the investigation of such hybrid mechanism is interesting.

Srivastava, & Sarkar, 2018). Therefore, the focal firm could benefit more in relying on external inventors' collective search, which is enabled by its patent abandonment strategy, when subsequent development of the patent requires recombination with more distant knowledge.

The above logic leads to the following hypothesis:

> *H1: The larger the distance between the focal firm's existing knowledge base and the knowledge that is used to develop the external inventors' invention within the knowledge spillover pool of the focal firm's abandoned patent, the more likely the focal firm integrates such an invention in its subsequent inventions.*

The economic value of the focal firm's patent abandonment strategy can also be created when the focal firm can rely on collective search to identify new partners. The invention within the knowledge spillover of the focal firm's abandoned patent that is created by a "new-to-firm" external inventor can typically create more economic value to the focal firm. New external inventors, who might be outside of the focal firm's existing knowledge field, can generate and develop new perspectives on a problem, which increases the possibilities of successful commercialization of inventions (Jeppesen & Lakhani, 2010). The focal firm's patent abandonment strategy provides it the opportunity to go beyond its currently accessible exchange partners and to obtain access to technologies and markets needed for innovative success (Alexy, George, & Salter, 2013). Without the focal firm's patent abandonment, these external inventors with relevant technological knowledge may not even be revealed to the focal firm. It is almost impossible for the focal firm's decision makers to acquire or contract for the requisite knowledge if they do not know where the knowledge is distributed and who can develop the technology (Felin & Zenger, 2014).

Further, the costs of acquiring the knowledge form a new exchange partner are usually higher than that of acquiring from a familiar exchange partner. Firms typically rely

on collaborating with a designated partner to deepen and broaden its knowledge base to better search for exploration and exploitation of its innovation (Yayavaram, Srivastava, & Sarkar, 2018). However, when the cost of searching and coordinating with specific exchange partners become high, the traditional mode of collaboration will not be efficient and effective for the focal firm to conduct its search strategy (Afuah & Tucci, 2012; Alexy, George, & Salter, 2013; Jeppesen & Lakhani, 2010). Under such circumstances, firms might rely more on collective search strategy to complement its search strategy through traditional mode of collaboration (Alexy, George, & Salter, 2013). The costs of collaborating with a designated exchange partner will be significantly reduced when more relational-specific assets are developed through recurrent collaboration. Therefore, the economic value of collective search will be high when the inventions are created with a new external inventor, which has no prior relationship with the focal firm.

> *H2: When the invention within the knowledge spillover pool is created by a "new-to-firm" external inventor, the focal firm is more likely to integrate this invention in its subsequent inventions.*

Although the focal firm can abandon its patent to motivate external inventors conducting collective search for subsequent development of its invention, which enables the focal firm to identify distant knowledge and new partners, the focal firm needs to have sufficient absorptive capacity concerning the knowledge spillover pool to integrate the invention in its subsequent inventions more efficiently and effectively. Thus, the focal firm is more likely to integrate the invention in its familiar area due to its superior absorptive capacity in such an area. The greater the technological strength in the area of the external inventor's invention, the more familiar the focal firm is to this invention, which makes it easier for the focal firm to learn and integrate in its subsequent inventions. Therefore,

H3: The positive relationship between the knowledge distance and the likelihood of the focal firm's invention integration is positively moderated by the focal firm's technological strength in the area of the external inventor's invention within the knowledge spillover pool.

H4: The positive relationship between the invention created by New-to-Firm Inventor and the likelihood of the focal firm's invention integration is positively moderated by the focal firm's technological strength in the area of the external inventor's invention within the knowledge spillover pool.

4.3 Methods

Sample and Data

I use patent citations to track the focal firm's inventions and as indicators of the external inventors' subsequent inventions in the knowledge spillover pool and focus on the semiconductor patents (NBER technological sub-categories code = 46).

The empirical work in this chapter is based on three datasets: First, I collect a list of abandoned patent in semiconductor category from USPTO Official Gazette, which provides expired patents weekly. Second, I obtain patent-level data from NBER patent dataset and Indiana & MIT patent database. Third, I use Compustat to obtain the financial data of each firm and merge the dataset with the patent level data. To minimize left- and right-censoring regarding the collection of patent data and to ensure access to firm financial data, I limit the sample to the patents that are abandoned between 1986 and 2001 (inclusive). Because I examine the effects of the focal firm's patent abandonment on its subsequent invention performance, I only keep firms in my sample that are active in patenting and patent abandonments and survive more than 10 years after it abandons the patent. Thus, I remove those firms that do not patent or abandon their patents for more than 5 years between 1986 and 2001 (inclusive). I also limit the sample firms to public firms to ensure the availability of financial data. An additional reason for non-inclusion of those

firms that are not publicly traded is due to evidence showing that many non-public organizations and individuals abandon their patents due to their lack of resources in patent management.[31] Through this process, the final sample includes 1,030 abandoned patents belonging to 69 firms, which generates 6,796 patents within the knowledge spillover pool.

Dependent variable

For each of the focal firm's patent abandoned in year t, I identify patents that are applied by external inventors and cite this abandoned patent during year t+1 and year t+5 (inclusive). The collection of such patents forms the knowledge spillover pool of the focal firm's abandoned patent, which is illustrated in Figure 3.1.

For each patent within the knowledge spillover pool, I measure *Invention Integration* as a binary variable, which equals 1 if the focal firm cites the patent in its subsequent inventions during year *t+6* to *t+10* (inclusive), and 0 otherwise.

Independent Variables and Moderator

For each patent within the knowledge spillover pool, I use the index created by Jaffe (1986) to measure the *Distance* between the knowledge used by external inventors in developing the focal firm's abandoned patent and the focal firm's existing knowledge base. The *Distance* index is calculated as:

$$Knowledge\ Distance = 1 - \sum_j d_j\, e_{ij} / [\left(\sum_j \left(d_{ij}\right)^2\right)^{\frac{1}{2}} \left(\sum_j \left(e_{ij}\right)^2\right)^{\frac{1}{2}}]$$

[31] See https://patinformatics.com/are-small-entities-more-likely-to-abandon-us-granted-patents-than-large-ones/

Where d_{ij} represents the fraction of firm *i*'s patents that are in patent class *j* and applied within five years before its patent abandonment. e_{ij} represents the fraction of the patents that are within the patent class j and are used by external inventors in creating the patents within the knowledge spillover pool. This measure is bounded between 0 and 1, with larger values representing increasing distance.

The second independent variable *New-to-Firm Inventor's Invention* reflects whether the focal patent within the knowledge-spillover pool is created by a *New-to-Firm Inventor,* which is a binary variable. I define a *New-to-Firm Inventor* as an external inventor that the focal firm has never cited any of this inventor's patents in prior inventions. If the patent is applied by a *New-to-Firm Inventor,* the construct equals 1, and 0 otherwise.

I measure the focal firm's *Technological Strength* in the area of the external inventor's invention as the citation-weighted number of patents that the focal firm applied in the area of the external inventor's invention.

Control Variables

Pool Quality

I use the number of forward citations a patent receives as a measure of patent quality (Trajtenberg, 1990). For each abandoned patent, I identify all the patents within the knowledge spillover pool. I then identify all the forward citations of this stock of patents received by 2010. The *Pool Quality* of is measured as the number of these forward citations. I divided this variable by 1,000 to reduce the scale.

Number of External Inventors

The *Number of External Inventors* within the knowledge spillover pool created through the focal firm's patent abandonment reflects how many external inventors are

motivated to conduct collective search for subsequent development of the focal firm's abandoned patent. I measure the construct as the total number of assignees (excluding the focal firm) for the patents in the knowledge spillover pool that is created through the focal firm's patent abandonment.

Current Ratio

The construct is used to reflect the availability of the focal firm's slack resources, which could enhance its innovation capabilities, and learning from the knowledge spillover pool of the abandoned patent (Yang, Phelps, & Steensma, 2010). I calculate the *Current Ratio* as current assets over current liabilities.

Firm Size

Prior research studies have shown that a firm's size will influence both the patent abandonment decision and learning from the knowledge spillover pool. On the one hand, a smaller firm is more likely to rely on external search in developing their innovation due to a lack of resources for subsequent exploitation and exploration of its patent. On the other hand, a smaller firm may lack absorptive capacities to capture value through developing new patents through learning from the knowledge spillover pool that is created by its abandoned patent. I apply the number of employees to measure *Firm size*. To reduce the scale, I divide the variable by 10^6.

Firm Diversification

A technologically diversified firm has a broader knowledge base and may be more likely to learn from the knowledge spillover pool in its subsequent invention. However, it is also possible that a technologically diversified firm will have less incentive to rely on external inventors' subsequent development of its technology due to its superior internal

search capabilities. Following Yang and colleagues (2010), I measure Firm Diversification in year t-1 as the Herfindahl-type index:

$$Firm\ Diversification_{it-1} = [1 - \sum_{j} \left(\frac{N_{jit-1}}{N_{it-1}}\right)^2] \times \frac{N_{it-1}}{N_{it-1} - 1}$$

where N_{jit-1} represents the number of patents of patent class j in firm i's patent stock at year $t-1$, and N_{it-1} represents the total number of patents that are in firm i's patent stock at year $t-1$.

Open Innovation

I define the focal firm's tendency in conducting *Open Innovation* as the extent to which the focal firm's innovation activities are based on external knowledge. I define external knowledge as backward citations made to the focal firm's overall patent stock that are not belong to the focal firm's own patents.

Explorative Search Paths

Following Lowe and Velosso (2015), I measure the focal firm's *exploratory search paths* in creating the focal firm's patent as the percentage to which a patent draws on knowledge outside the focal firm's existing knowledge base. Similarly, following Benner and Tushman (2002), and Lowe and Velosso (2015), this chapter defines the knowledge outside the focal firm's existing knowledge base as backward citations made to the patent, which are neither one of the firm's own patens, nor a patent cited previously by the focal firm in another of the firm's patents.

Internal Usage

I use the *Internal Usage* to measure a focal firm's absorptive capacity concerning its abandoned patents. For each focal patent that has an assignee code,[32] I first define self-citations as patents that have the same assignee code with the focal patent and that cite the focal patent. Second, I count the number of self-citations that the focal patent receives 4-years before it is abandoned. The construct *Internal Usage* is measured as the ratio of the focal firm's self-citations of the abandoned patent to the total citations of the patent.

Self-Owned Comp.

Following Toh and Miller (2017), I define the complementary patents as those patents that are jointly cited with a focal firm's abandoned patent and belong to different patent classes with the focal firm's abandoned patent. The *Self-Owned Complementary Patents* construct (*Self-Owned Comp.*) is measured as the percentage of complementary patents of the abandoned patent that is owned by the focal firm. I only keep the active complementary patents and remove those that are expired or abandoned by the focal firm.

Patent Scope

Prior research studies have shown that broader patents will tend to block more subsequent inventions that are derived from those patents (Huang & Murray, 2009). As a result, the focal firm's abandonment of its broader patent is more likely to generate a larger knowledge spillover pool, which makes it more likely that the focal firm will learn. Following Huang and Murray (2009), I measure the scope of each patent as the number of patent classes that are assigned to that patent.

[32] In the current research, I use the "lpermno" code in the *Indiana & MIT* patent database to identify the each patent assignee.

Technology Maturity

The construct has two competing impacts on learning from the knowledge spillover pool. On the one hand, the patent that contains more mature technology is easier to understand, which facilitates subsequent learning. On the other hand, the patent that contains mature technology is less uncertain when it is abandoned, which lowers the focal firm's incentive to track the development of its abandoned patent. Following Alnuaimi and George (2016), I measure *Technology Maturity* as the ratio of backward citations of focal patent to the number of claims the focal patent makes.

Abandon Stage

As mentioned in Chapter 2, in the United States, patent holder is required to pay three maintenance fees after the issuance of the initial patent. The longer the firm holds the patent, the more familiar the focal firm is for the abandoned patent, which contributes to the high absorptive capacity. However, at the same time, there would be fewer opportunities for the focal firm to learn from the knowledge spillover pool. I add two control variables, which is Abandon Stage_2nd and Abandon Stage_3rd to control different stages of the focal firm's patent abandonment.

Empirical Results

Because the dependent variable of this chapter is a binary variable, I use a logit model with firm- and year-fixed effects. Table 4.1 presents descriptive statistics and the correlation matrix for all of the variables.

Table 4.2 presents the empirical results of hypotheses tests for the probability of *Invention Integration*. Model 1 includes only control variables. Model 2 introduces the variable *Knowledge Distance* to test Hypothesis 1. The coefficient of *Knowledge Distance*

is positive and significant ($\beta = 0.751$, $p = 0.067$). The coefficient shows that a 1% increase in the *Knowledge Distance* between the knowledge used in creation the invention and the focal firm's existing knowledge base increases the likelihood of *Invention Integration* by 11.84%. The empirical results corroborate Hypothesis 1.

Model 2 incorporates the variable *New-to-Firm Inventor's Invention* to test Hypothesis 2. The coefficient is significantly positive ($\beta = 0.411$, $p = 0.000$). The positive coefficient suggests that when the invention is created by a *New-to-Firm Inventor*, the likelihood of Invention Integration is expected to increase by 50.81%, which provides support for Hypothesis 2.

Model 3 includes the interaction term between *Knowledge Distance* and the focal firm's *Technological Strength* to test Hypothesis 3. The coefficient of the interaction term is significantly negative ($\beta = -7.140$, $p = 0.003$), which is inconsistent with the prediction of Hypothesis 3. However, the marginal effect of an interaction between two variables in the nonlinear model is not simply the coefficient for their interaction term (Hoetker, 2007). Therefore, I use graphical presentations to better interpret the result (Yayavaram, Srivastava, & Sarkar, 2018). First, I graphically examined the net effects of *Knowledge Distance* and the focal firm's *Technological Strength* on the likelihood of *Invention Integration* in the focal firm's subsequent invention activities. Figure 4.1(1) shows that the average marginal effects of Knowledge Distance on the probability of Invention Integration at different value of the focal firm's Technological Strength in the area of the invention within the knowledge spillover pool. As the graph shows, the effect of Knowledge Distance is positively moderated by the focal firm's Technological Strength, which provides support to Hypothesis 3.

Second, in Figure 4.1(2), I decompose the interaction term and conduct simple slope analysis. I consider two multiple levels of the focal firm's *Technological Strength* in the invention technological area, as low and high. A low value of *Technological Strength* indicates that the results keep the value of one standard deviation below the sample's mean, while all the other variables are taken at their mean values (Hoetker, 2007). By contrast, a high value *Technological Strength* indicates that the value is one standard deviation above the sample's mean. Figure 4.1.2 shows that the line is steeper when the *Technological Strength* is at high level than when it is at low level, hence providing further support for Hypothesis 3.

Model 4 include the interaction term between *Technological Strength* and *New-to-Firm Inventor's Invention* to test Hypothesis 4. Similarly, I use graphical methods to examine the interaction effects. The graphical results in Figure 4.2.1 and 4.2.2 provide support for Hypothesis 4.

4.4 Conclusions

This chapter examines how the focal firm can use its patent abandonment to complement its existing search strategy. This chapter suggests that the focal firm's patent abandonment decision is not only a choice between continuing and terminating a line of research, but also could be a transformation of search strategy for subsequent development of its under-developed technology. The focal firm's patent abandonment can transform its limited internal search into external inventors' collective search. Relying on such a collective search, the focal firm can search distant knowledge and potentially new exchange partners in a more cost-effective manner, which can facilitate its future inventions. However, due to the focal firm's bounded rationality and path-dependence

search behavior, the focal firm's reliance on the external inventors' collective search is more likely to be restricted in the area where the focal firm has technological strength.

This chapter has several strategic implications. When the focal firm lacks resources and capabilities to search efficiently and effectively for further development of its patent, it can strategically abandon its patent to motivate external inventors to collective search. The collective is especially relevant if the cost for the focal firm to conduct internal search or collaborate with external inventors through traditional mode does not comparatively work well (Alexy, George, & Salter, 2013). The external inventors with relevant knowledge can self-motivate working in the area of the focal firm's abandoned patent. The focal firm, in turn, might identify the distant knowledge and potentially new partners in a more cost effective manner to facilitate its future inventions. This chapter further shows that the focal firm's prior technological strength might also contribute to its absorptive capacity concerning patents within the knowledge spillover pool, which significantly influences the focal firm's effectiveness in relying on external inventors' collective search in a specific area of knowledge.

As with many empirical studies, there are several limitations of this chapter, which provides opportunities for future research. First, this chapter does not distinguish the initial *strategic intent* of the focal firm's patent abandonment. This chapter suggests that all the focal firms are likely to search in the knowledge spillover created through its patent abandonment. However, in reality, it is possible that the focal firm's patent abandonment reflects its decision on project termination (Khanna, Guler, & Nerkar, 2018). Therefore, the focal firm might also abandon other complementary assets, while abandoning its patent. Under such circumstances, the focal firm might not give attention to the know-ledge

spillover pool of its abandoned patent any more. Future research -- perhaps through qualitative methods – can triangulate to examine how the focal firm's different motivations in patent abandonment can influence its subsequent inventions.

Second, this chapter cannot fully address the selection issues. The focal firm's patent abandonment could motivate external inventors self-select joining the knowledge spillover pool to collective search for development of the focal firm's abandoned patent. Therefore, participation in collective search does not occur randomly, but is instead predicted on endogenous choices made by external inventors. In the future, one can identify all the potential external inventors that exert effort in the development of the focal firm's patent to control for the sample selection bias.

Tables and Figures

Table 4.1: Summary Statistics

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	DV	1.00																
2	Knowledge Distance	0.28	1.00															
3	New Inventor	-0.12	-0.07	1.00														
4	Tech Strength	-0.11	-0.04	0.16	1.00													
5	Pool Quality	0.06	0.07	-0.13	0.03	1.00												
6	# of External Inventors	0.30	0.66	-0.04	-0.01	0.07	1.00											
7	Current Ratio	0.06	0.15	-0.03	0.07	0.03	0.12	1.00										
8	R&D	0.15	-0.02	-0.18	-0.27	0.12	-0.03	-0.01	1.00									
9	#of Employee	-0.15	-0.11	0.02	0.36	0.10	-0.07	0.00	-0.27	1.00								
10	Firm Diversification	-0.03	-0.06	0.08	0.50	0.01	-0.05	0.03	-0.43	0.57	1.00							
11	Open Innovation	0.07	0.00	-0.09	-0.01	-0.01	-0.02	-0.02	0.12	-0.13	0.00	1.00						
12	Explore	0.19	0.04	-0.17	-0.46	0.10	0.02	-0.02	0.78	-0.52	-0.66	0.12	1.00					
13	Internal Usage	0.07	0.03	-0.06	-0.23	0.09	-0.01	-0.06	0.03	-0.01	-0.12	-0.02	0.34	1.00				
14	Self-Owned Comp.	0.27	0.28	-0.17	-0.15	0.11	0.20	0.04	0.24	-0.14	-0.10	0.07	-0.25	0.09	1.00			
15	Patent Breadth	0.14	0.27	-0.26	-0.12	0.22	0.17	0.16	0.17	-0.01	-0.09	-0.03	0.19	0.10	0.33	1.00		
16	# of Inventors	0.01	-0.03	0.03	0.03	-0.07	0.03	-0.02	-0.02	0.07	0.05	0.02	-0.06	-0.06	-0.03	-0.06	1.00	
17	Tech maturity	0.10	0.08	-0.06	-0.07	0.01	0.05	-0.00	0.18	-0.17	-0.12	0.09	0.28	0.10	0.15	0.02	-0.01	1
	Mean	0.080	0.573	0.307	0.351	0.215	6.179	1.491	46.621	159.45	0.160	0.876	0.036	0.390	0.068	1.056	2.766	0.995
	S.D.	0.271	0.211	0.461	0.249	0.231	4.664	0.514	98.048	106.01	0.046	0.043	0.168	0.488	0.073	0.358	2.074	1.489
	Min	0	0.05	0	0	0.01	1	0.492	7.15	3.223	0.058	0.058	0	0	0	1	1	0.005
	Max	1	1	1	0.692	1.095	25	5.077	1462.5	321.527	0.562	0.562	1	1	0.762	7	28	32

Table 4.2: Logit Regression Results

	(1)	(2)	(3)	(4)	(5)
Independent Variables					
Knowledge Distance		**0.751***	**0.677***	**4.035*****	**0.688***
		(0.393)	**(0.390)**	**(1.346)**	**(0.392)**
New-to-Firm Inventors			**0.411*****	**0.404*****	**0.700****
			(0.117)	**(0.118)**	**(0.322)**
Moderator Variable				**-7.140*****	
Knowledge Distance				**(2.424)**	
* Technological Strength					**-0.662**
New-to-Firm Inventors					**(0.664)**
* Technological Strength					
Technological Strength	3.834***	4.243***	4.403***	8.222***	4.698***
	(0.871)	(0.990)	(0.997)	(2.005)	(1.062)
Control Variables					
Pool Quality	0.015	0.202	0.079	0.033	0.068
	(0.055)	(0.549)	(0.543)	(0.548)	(0.543)
# of External Inventors	0.028	0.023	0.016	0.022	0.017
	(0.020)	(0.020)	(0.020)	(0.021)	(0.020)
Current Ratio	2.216***	2.304***	2.345***	2.727***	2.368***
	(0.360)	(0.370)	(0.363)	(0.350)	(0.352)
R&D	0.002	0.002	0.002	0.001	0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
# of Employees	0.018***	0.018***	0.018***	0.020***	0.018***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Firm diversification	3.140	2.648	2.871	6.216**	3.088
	(3.145)	(3.239)	(3.174)	(2.952)	(3.103)
Open Innovation	-13.745***	-13.807***	-14.353***	-15.116***	-14.692***
	(4.243)	(4.485)	(4.432)	(3.866)	(4.465)
Explore	-0.442	-0.418	-0.552	-0.543*	-0.549*
	(0.281)	(0.282)	(0.286)	(0.286)	(0.286)
Internal usage	0.694***	0.684***	0.713***	0.729***	0.706***
	(0.119)	(0.119)	(0.120)	(0.121)	(0.120)
Self-Owned Comp. Patents	2.798***	2.693***	2.556***	2.529***	2.601***
	(0.574)	(0.577)	(0.580)	(0.584)	(0.585)
Patent Scope	-0.512**	-0.519**	-0.526**	-0.514**	-0.521**
	(0.256)	(0.258)	(0.258)	(0.241)	(0.254)
# of Inventors	0.006	0.006	-0.022	-0.007	-0.002
	(0.023)	(0.022)	(0.026)	(0.023)	(0.023)
Technology Maturity	-0.017	-0.028	-0.002	-0.030	-0.025
	(0.032)	(0.033)	(0.023)	(0.032)	(0.032)
Abandon Stage_2nd Stage	0.222*	0.151	0.156	0.147	0.154
	(0.133)	(0.142)	(0.143)	(0.143)	(0.142)
Abandon Stage_3rd Stage	-0.035	-0.033	-0.008	-0.037	-0.012
	(0.149)	(0.159)	(0.160)	(0.149)	(0.160)
Constant	0.774	0.305	0.499	-2.231	0.564
	(4.211)	(4.368)	(4.290)	(3.074)	(4.250)
Firm Dummies	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes
Psuedo R^2	0.296	0.298	0.302	0.305	0.302
N	6796	6796	6796	6796	6796

Table 4.3 Summary of Empirical Results

DV	IV	Theoretical Prediction	Empirical Finding
Whether the invention within the knowledge spillover pool is integrated by the focal firm in its future inventions	**H1:** *Knowledge Distance*	+	+
	H2: *New-to-Firm Inventor*	+	+
	H3: *Knowledge Distance * Focal firm's Technological Strength*	+	+
	H4: *New-to-Firm Inventor*Focal firm's Technological Strength*	+	+

Figure 4.1(1): Average Marginal Effects (AME) of *Knowledge Distance* on the probability of the focal firm's *Invention Integration* at different values of its *Technological Strength*

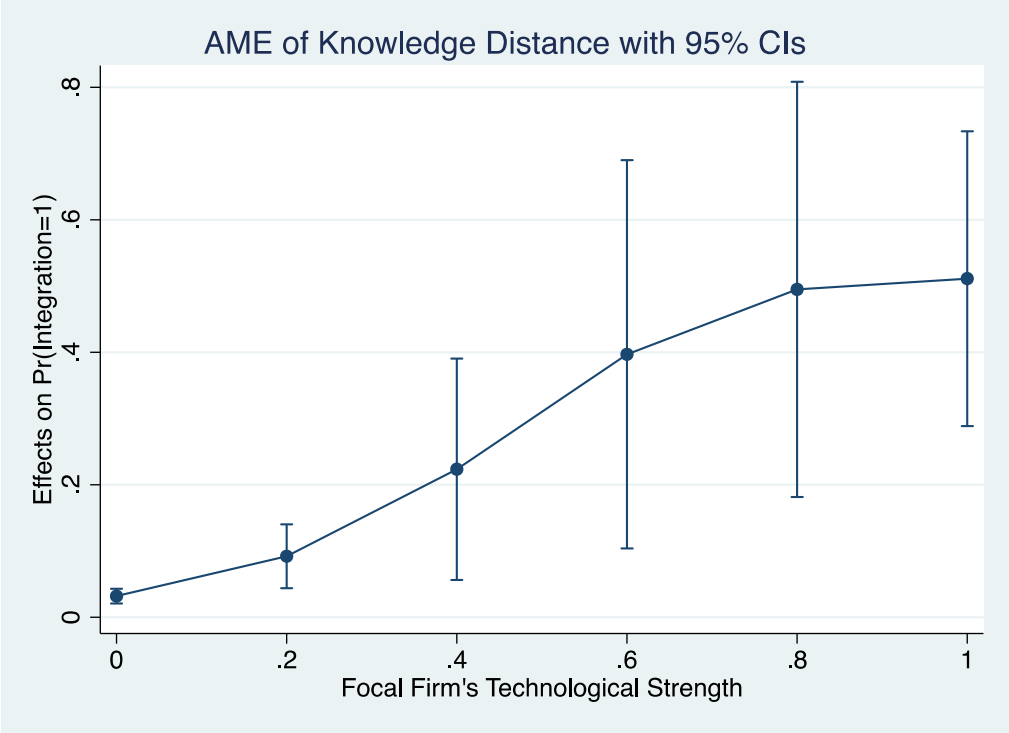


Figure 4.1(2): Moderating effect of the focal firm's *Technological Strength*

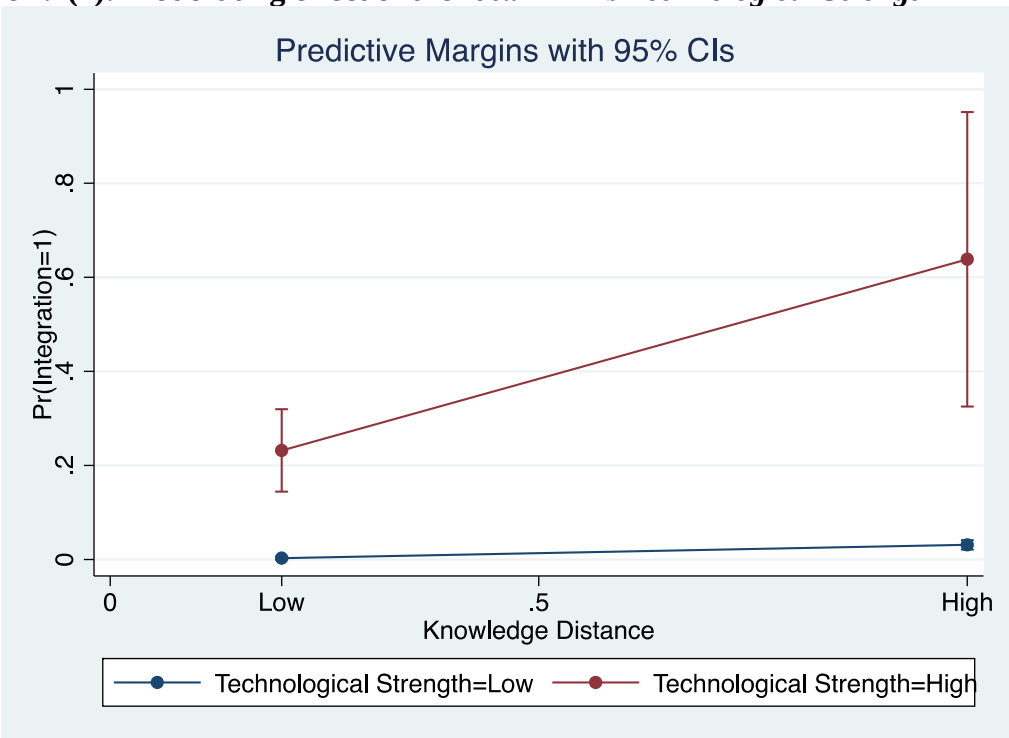


Figure 4.2(1): Average Marginal Effects (AME) of *New-to-Firm Inventor's Invention* on the probability of the focal firm's *Invention Integration* at different values of its *Technological Strength*

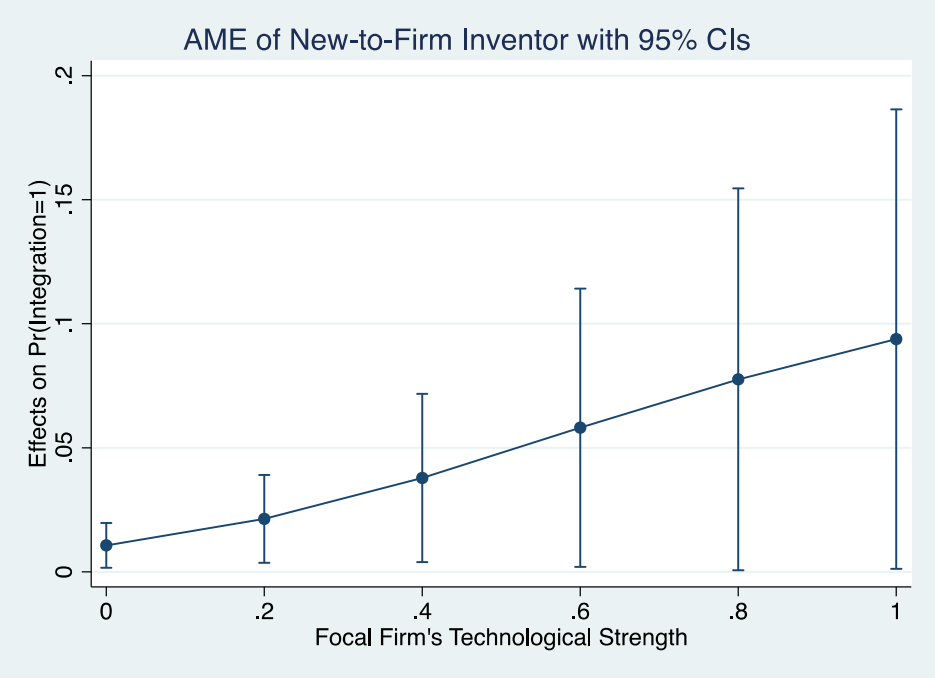
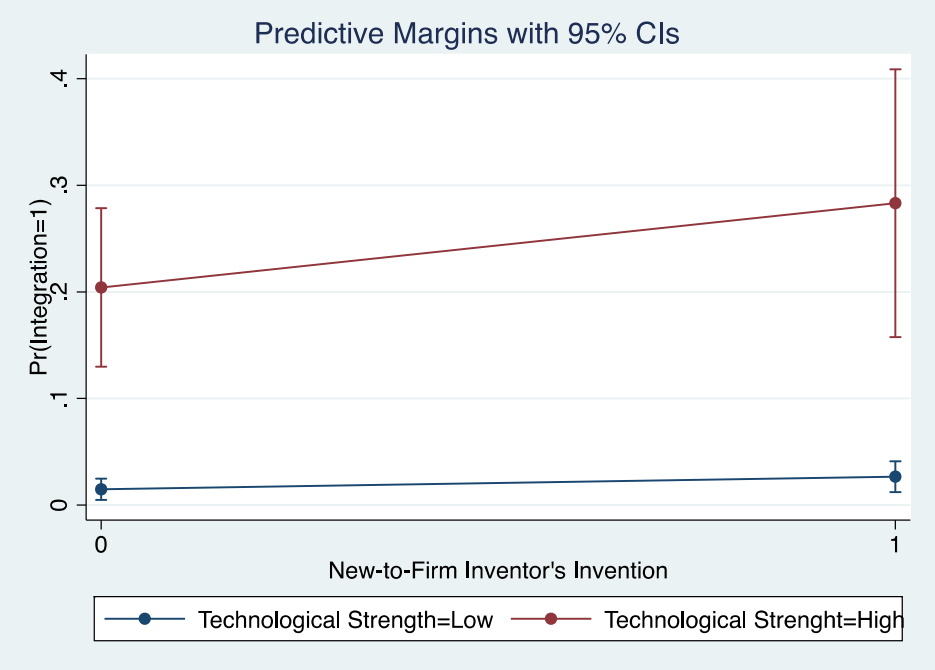


Figure 4.2(2): Moderating effect of the focal firm's *Technological Strength*



CHAPTER 5: CONCLUSION

The objective of this dissertation is to explain and predict the value creation and value capture of the focal firm's patent abandonment. The data show that, from a population of about 1.2 million patents issued by the USPTO, which were applied by firms between 1981 to 2010 (inclusive), firms abandon about 40% of these patents before their statutory expiration date (of 20 years after the priority -- i.e., effective filing -- date), based on firms' decisions to decline paying maintenance fees. The existing literature illustrates that the focal firm typically abandons its patent based on its anticipation of the low economic value of the patent, which is influenced not only by its internal resources and capabilities, but also by external technological developments and market conditions (Liu, Arthurs, Cullen, & Alexander, 2008; Lowe & Veloso, 2015). Furthermore, the neoclassical economic literature assumes that the focal firm's patents cannot create economic value to this firm after these patents are abandoned. This dissertation relaxes this assumption in the existing patent renewal and abandonment literature (Pakes, 1986; Serrano, 2010) and examines the development of cumulative inventions by external inventors, as well as the focal firm, after the focal firm's patent abandonment.

Across the three empirical chapters, I seek to offer an alternative explanation of why the focal firm might obtain positive economic value creation and value capture through abandoning its patent. I combine anti-commons theory, innovation search theory, and organizational learning theory to show that the focal firm's patent abandonment can (i) increase the amount and the breadth of the external inventors' cumulative inventions that build on the focal firm's abandoned patent and (ii) enable the focal firm to obtain

positive value capture by providing it opportunities for learning from the knowledge spillover pool created through its patent abandonment.

Chapter 2 examines how the focal firm's patent abandonment will influence external inventors' cumulative inventions that build on the focal firm's abandoned patent. Through a difference-in-differences estimation, I provide empirical evidence showing that the focal firm's patent abandonment will increase both the amount and the breadth of annual external forward citations of the abandoned patents, which is consistent with the "anti-commons" theory addressed in the extant literature (Galasso & Schankerman, 2011, 2015: Murray & Stern, 2007). The empirical results of Chapter 2 suggest that the focal firm's patent is possible to realize more of its technological and market value after its patent is abandoned through motivating external inventors to conduct more and broader research and development in the area of the abandoned patent. Therefore, the existing literature might underestimate the value of the focal firm's patent abandonment. The results of Chapter 2 are shown in Figure 5.2.

While Chapter 2 shows that the external inventors might benefit from the focal firm's patent abandonment, Chapter 3 and Chapter 4 seek to show that invention development process is not necessarily a zero-sum game, but, rather, is a positive sum game, in which the focal firm can also obtain positive value capture from its patent abandonment. Conventional wisdom suggests that, when the focal firm's abandoned patent is later revealed by others to have high technological and market value, the firm is *defined* to have made an "error" in judgment. The focal firm might lose millions of dollars in patent monetization because of such an "error" in judgment. Chapter 3 and Chapter 4 provide an alternative mechanism showing that the focal firm, instead of just viewing the subsequent

unexpected usage of its abandoned patent by external inventors as negative consequences, can consider some positive perspectives of abandoning its patent. The theory developed in this dissertation is that the focal firm could substantially benefit from abandoning its patent if this (strategic) move can motivate potential external inventors to create a more valuable knowledge spillover pool than would exist if the focal firm's patent were renewed, and this focal firm can then successfully develop more valuable cumulative inventions than the original abandoned patent through learning from these external inventors within this knowledge spillover.

Behavioral economics suggest that the focal firm, being boundedly rational, typically exhibits limited search in both exploration and exploitation of its invention. I submit that the focal firm's patent abandonment can motivate external inventors with relevant knowledge to self-select to work on the area of the abandoned patent, which transforms the focal firm's limited search in exploitation and exploration of its invention into external inventors' collective search. The transformation of the focal firm's search pattern in subsequent invention development can facilitate knowledge generation and entail lower costs in search for such development not only for external inventors, but ultimately for the focal firm as well. The focal firm can also learn from these external inventors to improve its subsequent inventions in a more cost-effective manner. Further, the focal firm often spends large amounts of resources in the initial discovery stage and subsequent development stage, which can contribute to its strong absorptive capacity (Cohen & Levinthal, 1990) and development of complementary assets (Teece, 1986). Therefore, the focal firm, though having abandoned the patent, can comparatively quickly and efficiently become familiar with patents in the knowledge spillover pool derived from its abandoned

patent (Yang, Phelps, & Steensma, 2010) and learn from external inventors in subsequent development of its abandoned patent.

Chapter 3 examines under what conditions the focal firm can learn from the knowledge spillover pool, which is important for the focal firm to create and capture value through its patent abandonment. Chapter 3 posits that a more valuable knowledge spillover pool created by external inventors through the focal firm's patent abandonment can provide the focal firm greater opportunities in subsequent learning and enable the focal firm to develop more inventions that build on the patents within the knowledge spillover pool. Further, the focal firm's absorptive capacity, open innovation experience, and holding of complementary patents would affect the focal firm's learning efficiency and effectiveness from the valuable knowledge spillover pool. The empirical work builds on data on patent abandonment in the semiconductor industry. The empirical results first show that the focal firm can develop more cumulative inventions that build on patents within the knowledge spillover pool when the knowledge spillover pool contains higher quality patents and more external inventors. Second, the inferior absorptive capacity due to the focal firm's explorative search paths in creating the patent impede the focal firm's learning from a more valuable knowledge spillover pool. Third, the focal firm's prior internal usage of the abandoned patent contributes to its building of strong absorptive capacity, which facilitates its learning from the knowledge spillover pool with high quality patents, but not with more inventors. Fourth, the focal firm's prior experience in external sources of inventions increases the focal firm's learning from a more valuable knowledge spillover pool. Finally, the focal firm's holding of more complementary patents have a statistically insignificant

effect on its learning from a more valuable knowledge spillover pool. The results of Chapter 3 are shown in Figure 5.3.

The empirical findings of Chapter 3 suggest that the focal firm can create and capture value from its patent abandonment by learning from the knowledge spillover pool. Chapter 4 further examines how the focal firm can use the patent abandonment to search knowledge for subsequent development of its inventions. In particular, I examine which patents within the knowledge spillover pool of the focal firm's abandoned patent are more likely to be integrated in the focal firm's subsequent inventions. I posit that the focal firm's patent abandonment can transform its limited internal search into external inventors' collective search. Relying on the collective search, the focal firm can search distant knowledge and potentially new inventors in a more cost-effective manner, which can facilitate its future inventions. However, due to the focal firm's bounded rationality and path-dependent search behavior, the focal firm's reliance on the external inventors' collective search is more likely to be restricted in the area where the focal firm has greater technological strength.

Similarly, the empirical work of Chapter 4 builds on the data of patent abandonment of the semiconductor industry. The empirical results are consistent with my theoretical hypothesis showing that the focal firm is more likely to integrate in its future inventions the external inventors' patents within the knowledge spillover pool that are: (1) recombined with knowledge distant from the focal firm's existing knowledge base, and (2) created by a *New-to-Firm* inventors. Furthermore, the focal firm's technological strength in the area of external inventors' patents within the knowledge spillover pool would positively moderate the focal firm's invention integration of patents recombined with

distant knowledge and created by *New-to-Firm* inventors. These findings suggest that the focal firm's patent abandonment the focal firm's patent abandonment decision is not only a choice between continuing and terminating a line of research, but also could be a transformation of search strategy for subsequent development of its under-developed technology. The empirical results of Chapter 4 are shown in Figure 5.4.

The dissertation has several strategic implications in terms of how the focal firm can use its patent abandonment strategy to create and capture value through facilitating cumulative inventions. The dissertation suggests that the focal firm, instead of just viewing the subsequent unexpected usage of its abandoned patent by external inventors as negative consequences, can consider some positive perspectives of abandoning its patent. When a patent requires further development to be commercialized, and the focal firm lacks resources, knowledge, and/or capabilities for such further development, it can strategically abandon its patent to motivate more external inventors with relevant resources, knowledge, and/or capabilities to develop the patent. The importance of such a strategic move is especially relevant if the traditional collaboration mode of licensing the technology does not comparatively work well due to a high level of exchange partner uncertainty, incentive misalignments, and coordination costs (Alexy, George, & Salter, 2013). For example, when the subsequent development of the original patent requires distant knowledge to the focal firm's existing knowledge base, or involved "new-to-firm" inventors, the focal firm might find it difficult to develop subsequent inventions efficiently through internal search or traditional mode of collaboration. Under such circumstances, the focal firm can abandon its patent to open the innovation process, which might enable the focal firm to identify distant knowledge and new inventors. The external inventors might turn the initial

economically non-viable patent into an economically valuable one through their further development. When the focal firm can learn from knowledge spillover pool comparatively quickly and efficiently, the potential negative spillovers created through its original patent abandonment can be mitigated through such learning effects (Agarwal, Audretsch, & Sarkar, 2007). In particular, if the knowledge spillover pool contains higher quality patents than the focal firm can develop itself through holding the patent, the focal firm can achieve positive value capture through its patent abandonment and subsequent learning.

The focal firm is more likely to abandon its patent for value creation and value capture when the focal firm has superior capabilities in identifying and internalizing knowledge from a valuable spillover pool created through its original patent abandon-ment. First, the focal firm is more likely to achieve positive value creation and value capture when abandoning patents developed through its exploitive search path than abandoning patents developed through its explorative search patent. Research studies concerning whether the focal firm would more likely to abandon explorative patents or exploitive patents show mixed results. Lowe and Veloso (2015) show that firms are more likely to abandon explorative patents because of the greater likelihood of the focal firm's failure in explorative search strategy. Khanna, Guler, and Nerkar (2018) submit that managers might avoid early termination of inventions in exploration area because the amount of information required to evaluate such inventions is not available at early decision points, especially when the inventions are interdependent with firm's other inventions. The dissertation maintains that due to the focal firm's inferior absorptive capacity concerning the explorative patent, as well as patents that build on this explorative patent by external inventors subsequently, the focal firm might not learn efficiently and effectively from the

knowledge spillover pool created through its explorative patent abandonment for value creation and value capture. Therefore, the empirical results of the dissertation suggest that firms would be less likely to abandon its explorative patents for value creation and value capture when they have fewer resources and capabilities in subsequent development of the patents.

Second, the focal firm is more likely to achieve positive value creation and value capture when abandoning patents when it has more internal usage. Nerkar and MacMillan (2003) find empirically that as the focal firm uses more of the patent internally in its subsequent research, the focal firm is less likely to abandon this patent until the firm reaches a point where it has exhausted all possibilities with the patent, after which the increase in internal use is positively associated with the likelihood of its abandonment. The dissertation provides further evidence showing that when the focal firm has greater internal usage of the patent with all possibilities, the focal firm can abandon the patent to rely on external inventors' search for the patent development. The focal firm's resources allocated in the development of the patent before its patent abandonment make it highly knowledgeable concerning this initial patent. Thus, when the focal firm abandons its initial patent it sets in motion a series of inventive responses by other firms, which due to the superior absorptive capacity of the focal firm can ultimately lead it to learn efficiently and effectively from the knowledge spillover pool of its abandoned patent. The extant literature has focused on the subsequent internal usage of the invention can generate new avenues for profiting from the original invention (Ahuja, Lampert, & Novelli, 2013). This dissertation shows that the internal usage of the patent before the patent abandonment might also enable the focal firm to profit from abandoning its patent.

Third, the dissertation shows that the focal firm's prior external knowledge sourcing experience would influence its effective usage of patent abandonment to create and capture value. The focal firm could open the innovation process to the public through abandoning its patent to identify distant knowledge and potential new exchange partners for subsequent inventions. To achieve positive value capture, the focal firm should posit sufficient capabilities to close the innovation process in its subsequent inventions. The focal firm's prior reliance on external sources of inventions in its invention activities enable the focal firm to build culture and capabilities in leveraging external sources of inventions into its future closed innovation.

Last, but not least, the dissertation shows that the focal firm might not capture the economic value created through its patent abandonment by holding more patents that are complementary. On the one hand, however, the focal firm's ownership of complementary patents increases its bargaining power in its subsequent learning from the knowledge spillover pool, which can also attenuate an economic holdup problem. On the other hand, the focal firm might also face high expropriation risk in disclosing its focal technology when holding complementary technologies. In particular, the external inventors might create a higher quality knowledge-spillover pool by utilizing a new set of complementary patents of the focal firm's abandoned patent. Under such circumstances, the focal firm might lose the advantage in learning from the knowledge spillover pool through owning the original complementary patents of its abandoned patent. Thus, the focal firm should be cautious in abandoning its patent, even though it has the ownership of a large amount of complementary assets.

5.1 Limitations and Future Research

As with many empirical research studies, there are several limitations of this dissertation, which provides opportunities for future research. First, this dissertation emphasized an underexplored motivation of the focal firm's patent abandonment. However, I cannot measure the exact motivation of the focal firm's patent abandonment. This dissertation cannot distinguish whether the focal firm's value creation and value capture from its patent abandonment is emergent or planned. Future research -- perhaps through qualitative methods – can triangulate to examine how the focal firm's different motivations in patent abandonment can influence its subsequent inventions.

Second, this dissertation only considers the focal firm's patent abandonment as a potential patent strategy in opening up its patent. In reality, some firms might choose to renew the patent, but make the patent free for the public to use (e.g., Tesla). Some examples are provided in Table 5.2 and Table 5.3. These strategies might correlate with each other. In future research, I plan to make a comparative assessment of impacts of the different focal firm's strategies in relinquishing its patents on its subsequent inventions. Furthermore, there can be some interaction between different mechanisms. For example, the focal firm can only abandon its patent in the 4^{th}, 8^{th} and 12^{th} years after the issuance of patent. However, the focal firm can announce to open up its patent at any time. If the focal firm publicly announced to open up its patent before the date for renewal and abandonment, the abandonment of the patent might not create as large a knowledge spillover pool as one might expect based on the empirical results reported in this chapter.

Third, this dissertation uses patent citations to measure knowledge spillovers and the focal firm's learning from the knowledge spillover, which is an imperfect measure.

Chapter 2 uses patent citations to measure knowledge spillovers. On the one hand, subsequent inventions can be non-patented, which thereby underestimates the cumulative inventions conducted by follow-on inventors. On the other hand, both examiners and applicants (Hegde & Sampat, 2009) can make the citation. Those that are made by examiners cannot be used to reflect knowledge spillovers. Ideally, citations made by examiners should be removed. However, these data are only available after 2001, which is not available for our sample. Chapter 3 and Chapter 4 use patent citations to reflect the focal firm's learning. On the one hand, using the focal firm's learning from the knowledge spillover pool likely underestimates its learning gains because I do not take into account its learning in terms of non-patented inventions. On the other hand, the focal firm's filing of new patents citing the patent of the knowledge spillover pool does not necessarily represent the focal firm's learning and technology advancement. The focal firm can file the patent for defensive or strategic reasons, which overestimates its learning gains from patent abandonment. Though I use a new measurement to deal with strategic patenting, it is by no means a perfect measure. Future research might develop a better measure for cumulative invention to obtain more detailed analysis of this issue (e.g., see Murray and O'Mahony (2007) for a review of cumulative innovation).

5.2 Contributions

In summary, this dissertation offers the following three contributions to the extant research literature in the *Strategy* field. First, the dissertation contributes to the intellectual property rights strategy literature. This dissertation examines how the focal firm can use its patent abandonment to balance value creation and value appropriation through facilitating cumulative inventions, which is less explored in the extant literature (Somaya,

2012). This research question addresses an important question in the *Strategy* field concerning *how a firm can create and capture value* (Nickerson, Silverman, & Zenger, 2007). Further, empirical results of this chapter suggest that the current patent renewal and abandonment literature might underestimate the economic value of the focal firm's abandoned patents to the society (Chapter 2), as well as to the focal firm (Chapter 3 and Chapter 4).

Second, this dissertation extends the literature on open innovation by combining literature on patent abandonment, organizational learning, and open innovation. Most of the open innovation literature focuses on the inbound open innovation side by examining how firms' inventions can benefit from relying on different external sources of know-ledge. However, the outbound open innovation side, which emphasizes the requirement of organizations to allow unused and underutilized ideas to go outside the organization for others to use, is less explored (Chesbrough & Chen, 2015; West & Bogers, 2014). This dissertation fills the research gap and this dissertation suggests that the focal firm can abandon its patents to motivate external collective search for its internal under-developed inventions. This dissertation further examines hybrid forms of innovation by emphasizing the importance of both open- and closed-innovation, and both the inbound and outbound innovation. The overall framework is presented in Figure 5.1.

Third, I seek to contribute to the knowledge spillover literature, which has addressed the importance of the focal firm's capability in internalizing knowledge spill-overs from its own innovation on its value capture (Belenzon, 2012; Jaffe, Trajtenberg, & Fogarty, 1993). The extant literature has discussed the determinants of the focal firm's learning from knowledge spillovers from its own original invention in its subsequent

inventions (Alnuaimi & George, 2016; Operti & Carnabuci, 2014; Yang, Phelps, & Steensma, 2010). As an extension, I focus on the focal firm's learning from a special type of knowledge spillover created through the focal firm's abandoning its patent. This dissertation shows that though the focal firm had abandoned its patent, it can still learn from the knowledge spillover pool created through its patent abandonment. Empirical results further show that the focal firm's existing knowledge stock, resource allocation, and experience in open innovation would enhance its learning from the knowledge spillover pool of its patent abandonment.

In conclusion, this dissertation examines the impact of the focal firm's patent abandonment on cumulative inventions created by external inventors, as well as the focal firm. Across three empirical studies, I provide an alternative explanation of why the focal firm can achieve positive value creation and capture through abandoning its patent. I hope that this research study proves fruitful for generating further theory refinements and econometric advances in our evolving strategy science.

Tables and Figures

Table 5.1: Summary of Empirical Chapters Main Findings

Chapter	Research Questions	Main Findings
Chapter 2 – The Impact of Patent Abandonment on Cumulative Inventions.	How does the focal firm's patent abandonment decision influence cumulative inventions derived from this abandoned patent?	- The focal firm's patent abandonment will increase both the amount and the breadth of external inventors' cumulative inventions that build on the focal firm's abandoned patent.
Chapter 3 – Firms' Patent Abandonments and Subsequent Inventions: Knowledge Spillover Pools, Absorptive Capacity, Open Innovation and Complementary Patents.	Under what conditions is a firm more likely to learn successfully from the knowledge spillover pool that is created by its patent abandonment?	1. An increase of the *quality* of knowledge spillover pool leads to an increase in the focal firm's cumulative inventions that build on external inventors' patents within this spillover pool. 2. An increase in *the number of external inventors* within the knowledge spillover pool leads to an increase in the focal firm's cumulative inventions that build on external inventors' patents within this spillover pool. 3. The focal firm's *explorative search paths* weakens the relationship between the value (determined by quality and number of external inventors) of the knowledge spillover pool and the focal firm's cumulative inventions that build on external inventors' patents within this spillover pool. 4. The focal firm's more *internal usage* of the abandoned patent strengthen the relationship between the value (determined by quality) of the knowledge spillover pool and the focal firm's cumulative inventions that build on external inventors' patents within this spillover pool. 5. The focal firm's *prior reliance on external sources of inventions* strengthen the relationship between the value (determined by quality) of the knowledge spillover pool and the focal firm's cumulative inventions that build on external inventors' patents within this spillover pool. 6. The focal firm's *self-ownership of complementary patents* has statistically insignificant moderating effect of the relationship between the value (determined by quality and number of external inventors) of the knowledge spillover pool and the focal firm's cumulative inventions that build on external inventors' patents within this spillover pool.

Table 5.1 (cont.): Summary of Empirical Chapters Main Findings

Chapter 4 – Firms' Patent abandonment and Search for Subsequent Inventions: Distant Knowledge, New-to-Firm Inventors and Technological Strength	Which type of patent within the knowledge spillover pool is more likely to be integrated in focal firm's subsequent inventions?	1. The larger the distance between the focal firm's existing knowledge base and the knowledge that is used to develop the external inventors' invention within the knowledge spillover pool of the focal firm's abandoned patent, the more likely the focal firm integrates such an invention in its subsequent inventions. 2. When the invention within the knowledge spillover pool is created by a "new-to-firm" external inventor, the focal firm is more likely to integrate this invention in its subsequent inventions. 3. The focal firm's technological strength in area of the external inventor's invention strengthens the positive effect of its knowledge integration of invention recombined with larger distance knowledge and created by New-to-Firm inventor.

Table 5.2: Firms' announcement of open up intellectual property rights

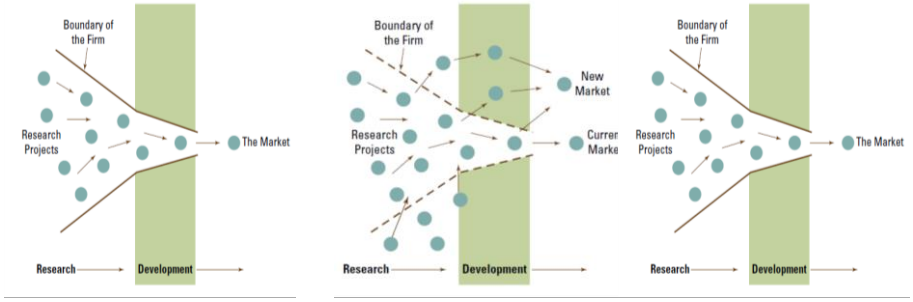
Institutions	Date	News	Title
NASA	10/7/2015	NASA's Technology Transfer program says it is opening up its patent portfolio and waiving the costs associated with using the patents for at least the first three years of a company's product development. Once a startup has brought the product to market, NASA will starting collecting a "standard net royalty fee," but otherwise inventors will be able to use the patents however they like.	NASA is opening up hundreds of patents to inventors, for free
Tesla	6/12/2014	Tesla will not initiate patent lawsuits against anyone who, in good faith, wants to use our technology.	All our patents belong to you
Toyota	1/5/2015	Toyota would open up its patent portfolio to drive wider adoption of hydrogen technology. Under the automaker's scheme, manufactures will be allowed to develop products using its patented technology through 2020 without a royalty fee.	Toyota to give away fuel-cell patents to boost industry
Ford	5/28/2015	Ford is opening its portfolio of electrified vehicle technology patents to competitive automakers to accelerate industry-wide research and development of electrified vehicles. To access Ford's patents and published patent applications, interested parties can contact the company's technology commercialization and licensing office, or work through *AutoHarvest* – an automaker collaborative innovation and licensing marketplace. The patents would be available for free.	A short history of giving away your patents
IBM	1/10/2005	IBM is making 500 of its software patents freely available to anyone working on open-source projects, like the popular Linux operating system, on which programmers collaborate and share code.	IBM to give free access to 500 patents
Google	9/8/2015	1. Startups can gain two non-organic patent families from *Google*, as well as the opportunity to buy more patents from the company at some point down the line. After startups are accepted into the program, *Google* will send a list of three to five families of patents and allow startups to pick two of them. 2. Startups must also join the *LOT Network*, which includes companies like *Dropbox* and *Canon* and focuses on stopping patent trolls. 3. The 2014 revenue for startups should be between $500,000 and $20 million.	Patent starter program
LG	2/4/2015	LG Group will share 29,000 patents with companies in bio-, energy- and beauty-related industries and make more of them free to start-ups in North Chuncheong Province where LG affiliates have operations.	LG to open 29,000 patents to ventures
Panasonic	3/24/2015	Panasonic Corp. will make about 50 of its patents available for royalty-free use in the development of the "internet of things." The Japanese electronics company said it will share its software and product experience in cloud computing technologies, such as connecting home monitoring and solar energy systems to the Internet.	Panasonic to open innovation to speed development of "Internet of Things"
Novell	10/12/2004	U.S. software giant Novell would not enforce any of its patents against Linux or the Open Source Software community.	

Table 5.3: Open collaboration initiatives

Initiative/ year/ participants	Technology	Details
Eco-Patent Commons/2008/ IBM, Nokia, Sony, Pitney Bowes, DuPont, Ricoh, Tasei Corporation, Xerox, and Bosch	Environmental friendly technologies	1. An initiative to create a collection of patents that directly and indirectly protect the environment. 2. Members give the patents to the Commons and pledge not to enforce their rights against anyone who choose to use the patents. 3. "Defensive termination": pledging firm can "terminate" the non-assertion pledge if a third party that uses a pledge patent asserts its own patent against the pledging company.
GreenXchange/2010/ Nike, Creative Commons, Best Buy	Patent and Know-how	1. *GreenXchange* is a web-based market place where companies share intellectual property rights developed by them to stir up innovation in industries in which they themselves do not compete. 2. Those wishing to post IP on the *GreenXchange* can choose to classify it under three different licensing structures. A standard option (offers *GreenXchange* users the chance to obtain a royalty free license under which they can commercially use the patented technology; in other words, the owner of the IP is willing to give it away and the users can utilize it however they wish). In addition, a standard PLUS option (gives *GreenXchange* users the opportunity to acquire a license that requires a payment and/or features restrictions), and a research non-exempt option (provides non-profits the opportunity to conduct research on the posted patented technology, improve and adapt it, and then patent these improvements and adaptations for non-commercial use).
BiOS (Biological Open Source)/2005/ Cambia	Research tools	Firms may use patented technologies (Research tools) royalty-free but agree to "share with all *BiOS* licensees any improvements to the core technologies as defined, for which they seek any IP protection" and "agree not to assert over other *BiOS* licensees their own or third-party rights that might dominate the defined technologies."
WIPO Re: Search initiative/2011/GlaxoSmithKline , Alnylam, AstraZeneca, Eisai, MSD, Novartis, Pfizer, Sanofi	Neglected Tropical Diseases, malaria, and tuberculosis	It provides a platform where firms and research institutions share their knowledge and IP regarding the treatment of NTO, malaria and tuberculosis.

Figure 5.1

Hybrid Forms of Innovation



Stage 1： Closed Innovation　　Stage 2: Open Innovation　　Stage 3: Closed Innovation

Figure 5.2

Empirical Results for Chapter 2

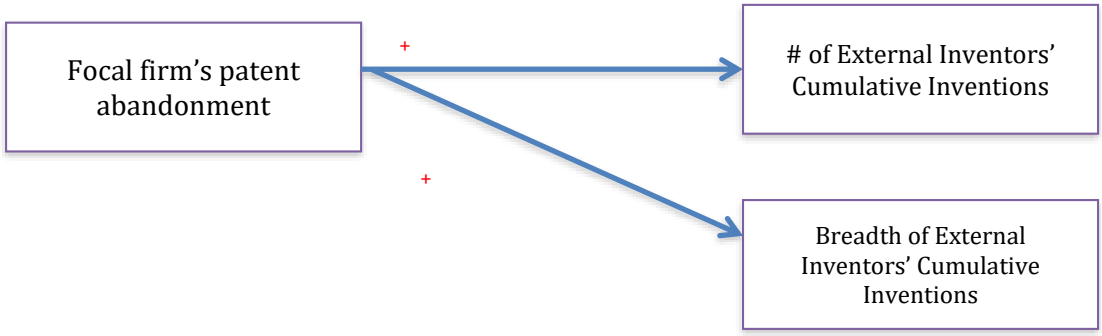
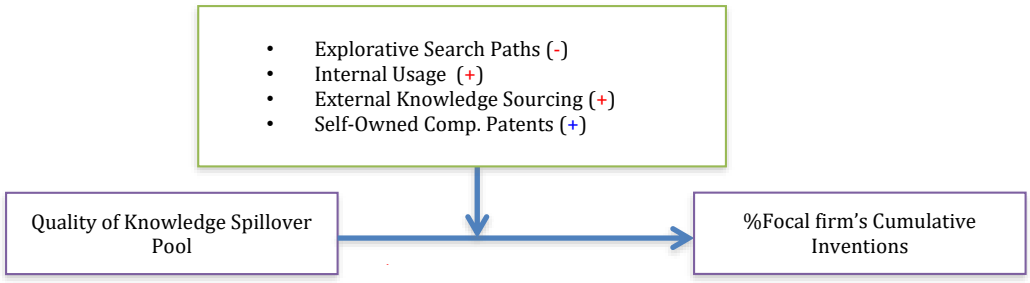


Figure 5.3

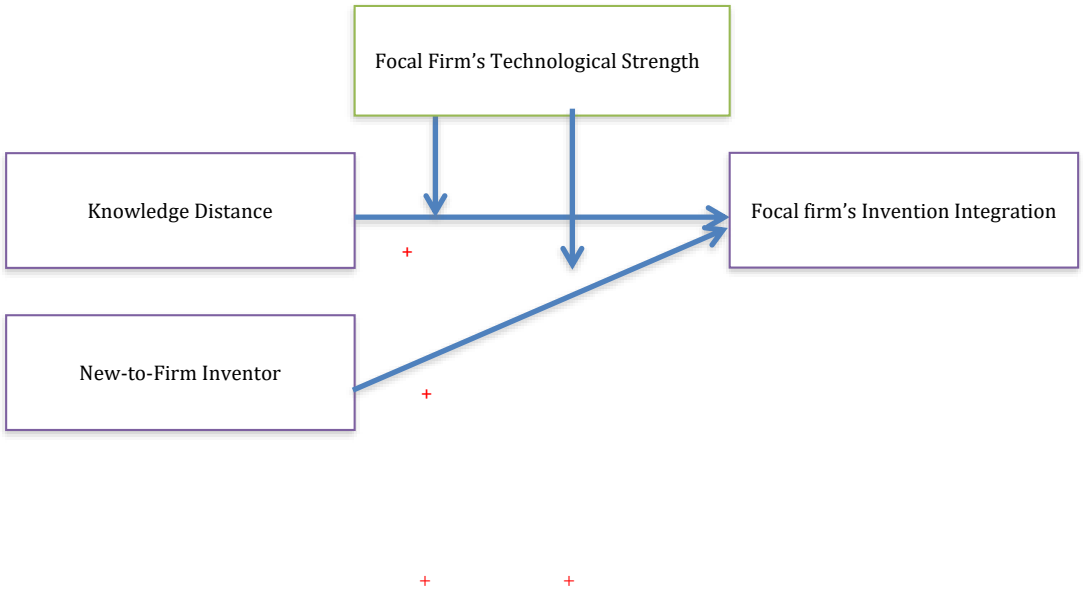
Empirical Results for Chapter 3



Note: The results shown in parentheses in red mean the results are corroborated empirically, while the results shown in parentheses in blue mean the results are not supported empirically.

Figure 5.4

Empirical Results for Chapter 4



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