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Does Firm-Originated Knowledge Matter? Diversity and Breakthrough Innovations

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Abstract

We examine how the firm-originated knowledge impacts the development of breakthrough innovations. While firm-originated knowledge reflects applied and context-dependent technologies, diverse firm-originated knowledge introduces novel and hybrid ideas, increases potential audiences, and reduces the risk of intellectual lock-in. We propose that incorporating firm-originated knowledge decreases the likelihood of an innovation becoming a breakthrough, whereas the diversity of firm-originated knowledge increases the likelihood of an innovation becoming a breakthrough; and the novelty generation partially mediates both of these effects. Our analysis of the U.S. nanotechnology patents filed between 1978 and 2004 offers support for our hypotheses. We thus identify an important mechanism by which firm-originated knowledge that is embedded in an innovation has dual impacts on the innovation to generate novelty and become highly valuable.

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ABSTRACT

We examine how the firm-originated knowledge impacts the development of breakthrough innovations. While firm-originated knowledge reflects applied and context-dependent technologies, diverse firm-originated knowledge introduces novel and hybrid ideas, increases potential audiences, and reduces the risk of intellectual lock-in. We propose that incorporating firm-originated knowledge decreases the likelihood of an innovation becoming a breakthrough, whereas the diversity of firm-originated knowledge increases the likelihood of an innovation becoming a breakthrough; and the novelty generation partially mediates both of these effects. Our analysis of the U.S. nanotechnology patents filed between 1978 and 2004 offers support for our hypotheses. We thus identify an important mechanism by which firm-originated knowledge that is embedded in an innovation has dual impacts on the innovation to generate novelty and become highly valuable.

Keywords: firm-originated knowledge, diversity, novelty, breakthrough innovations, knowledge source

INTORDUCTION

The positive role of university-originated knowledge in increasing the value of resulting innovations is well developed in the literature (Jaffe, 1989; Mansfield, 1990; Zucker, Darby, and Armstrong, 2002; Fleming and Sorenson, 2004; Zucker et al., 2007). However, the effect of firm-originated knowledge on successful innovative outcomes remains unexplored. Firm-originated knowledge—firm-generated knowledge that is embedded in innovations—may have different impacts on innovations from university-originated knowledge because, presumably, firms and universities generate knowledge of different natures. This assumption is reasonable because firms and universities pursue fundamentally different agenda: scientific research for universities and maximized appropriation for firms (Arora and Gambadella, 1994; Dasgupta and David, 1994; Gittleman and Kogut, 2003). We note that while firms endeavor to develop technologies and possess sufficient knowledge about status quo technologies (Nelson and Winter, 1982), there seems to be a consensus that firm-generated technological knowledge, in general, lacks superiority in providing theoretical guidance for future innovations (Rosenberg, 1990; Fleming and Sorenson, 2004). We complement this line of literature by proposing a mechanism by which firm-generated knowledge may contribute to generating breakthrough innovations.

The role of firm-originated knowledge in generating highly valuable innovations is ambiguous in literature because existing theories appear to yield contrasting predictions. In general, seeking for knowledge beyond a confined organizational boundary induces better innovative performance (Rosenkopf and Nerkar, 2001; Katila and Ahuja, 2002; Phene, Fladmoe-Lindquist, and Marsh, 2006; Lavie, Stettner, and Tushman, 2010; Chatterji and Fabrizio, 2014). Further, a significant body of literature suggests that spillovers of firm-originated knowledge have a positive effect on firms' knowledge stocks (Spence, 1984; Cohen and Levinthal, 1990), R&D productivity (Jaffe, 1986; Griliches, 1992), and innovation incentives (Ceccagnoli, 2005). On the other hand, Mansfield's (1991) finding that a significant portion of industrial innovations could not have been developed in the absence of related university research implies a lower utility of overall firm-generated knowledge in achieving subsequent innovations. Literature support this point by suggesting that, to increase capacity to exploit others' advanced knowledge, even firms need to learn from basic research rather than from applied technologies (Rosenberg, 1990; Cohen and Levinthal, 1990). Moreover, as firms tend not to disclose their core technologies and rather secure them as secrecy (Jaffe, 1989; Cohen, Nelson, and Walsh, 2000), firm-originated knowledge that is available as search targets may not include critical information that promotes the value of subsequent innovations.

To clarify the role of firm-originated knowledge in driving breakthrough innovations, we investigate the intensity and diversity of firm-originated knowledge that composes an innovation. Innovations typically embed prior-knowledge that has been developed in the past along technology development trajectories (Schumpeter, 1939; Nelson and Winter, 1982; Dosi, 1982; Kogut and Zander, 1992). Scholars have studied the prior-knowledge that innovations are based on from the standpoint of which boundaries the prior-knowledge belongs to (Rosenkopf and Nerkar, 2001); how mature the prior-knowledge is (Katila, 2002; Nerkar, 2003); and what scopes the prior-knowledge spans (Katila and Ajuja, 2002). More recently, burgeoning literature studies the effect of technological and geographical distances on the value of innovations (Capaldo, Lavie, and Petruzzelli, 2014) and dual effects of technological distance and diversity on the cognitive and economic value of innovations (Kaplan and Vakili, 2014). Yet, to the extent of our knowledge, we know little about what the effect of incorporating firm-originated knowledge is and how the diversity of firm-originated knowledge influences on the value of resulting innovations. This gap has generally lied outside purview of literature. For example, prominent research has paid attention to understand how knowledge adopted from upstream technologies such as those of university or public research affects downstream technology developments (Cohen, Nelson, and Walsh, 2002; Zucker, Darby, and Armstrong, 2002; Rothaermel and Thursby, 2005). Further, studies on knowledge adoption and innovation have mainly examined the distance and diversity based on technology classes between embedded prior-knowledge and resulting innovations (e.g., Fleming, 2001); or exploration and exploitation literature addresses the boundary-spanning of involved function domains, technology fields, and organizations, usually identifying the boundary by alliances (e.g., Lavie, Kang, and Rosenkopf, 2011). Thus, degree of diversity (i.e., concentration) of knowledge sources is still underexplored in explaining innovative performances.

In explaining the role of diverse individuals, researchers have documented significant advantages of diverse individuals in problem-solving and generating creative outcomes (Utterback, 1971; Simon, 1985; Hong and Page, 2004; Walsh and Nagaoka, 2009; Singh and Fleming, 2010). Diverse technical experiences or networks that each inventor brings into the work setting enhance inflows of outside technological information (Utterback, 1971) and promote technological breakthroughs (Singh and Fleming, 2010). As diverse knowledge structures facilitate problem-solving (Simon, 1985; Cohen and Levinthal, 1990), the diversity among individual perspectives and heuristics (Hong and Page, 2004) or among vertically-diffused collaborators (Walsh and Nagaoka, 2009) yields superior innovative outcomes. This line of research emphasizes the role of diverse inventors, which increase variations, in generating the set of possible solutions and effectively selecting the best alternative. However, these works leave the following question untested: does the diversity work only through diverse inventors to increase the variations in the input and to sharpen the selection among alternatives—that is being selected or perished—or does the diverse knowledge that is incorporated in an innovation persist also in the innovation and hence engender breakthroughs? Put differently, will an innovation embedded with diverse knowledge inputs be superior to others that are built on relatively homogenous knowledge? As firm-originated knowledge that is embedded in an innovation exhibits various degrees of diversity regarding to knowledge sources, we demonstrate how the diversity of firm-originated knowledge affects the value of the innovation.

To address this gap in literature, we focus on the relationship between relying on firm-originated knowledge and achieving highly valuable innovations, breakthroughs, because this small portion of innovations are critical in creating Schumpeterian rents and thus represents high economic value of innovations (Schumpeter, 1975; Trajtenberg, 1990; Harhoff, et al., 1999; Ahuja and Lampert, 2001). One stream of literature has emphasized the importance of novelty as a potential generator of breakthrough innovations (March, 1991; Phene et al, 2006; Singh and Fleming, 2010). Another stream of literature suggests that value of an innovation is only partially explained by novelty creation (Kaplan and Vakili, 2014). Accordingly, to reconcile two streams, we examine the mediating role of novelty creation in connecting firm-originated knowledge to breakthrough innovations.

We propose that incorporating firm-originated knowledge decreases the likelihood that resulting innovations become breakthroughs outcomes, whereas the diversity of firm-originated knowledge increases the likelihood of developing breakthrough innovations; and the novelty generation partially mediates both of these effects. Firm-originated knowledge is generally considered as applied and downstream-oriented (Bush, 1945), context-dependent (Arora and Gambardella, 1994), progressing along a "natural trajectory" (Nelson and Winter, 1977; Dosi, 1982), and with a view to an appropriation (Teece, 1986). Thus, with more firm-originated knowledge embedded in innovations, the innovations may reduce novelty creation, appropriability, and general usages, leading to being less likelihood of breakthroughs. On the contrary, diversity of firm-originated knowledge will increase the likelihood that an innovation generates novelty and thus breakthrough innovations by the introduction of new components and hybrid ideas. Further, as diverse firm-originated knowledge induces the benefit of potential various audiences and the low risk of intellectual lock-in, diverse firm-originated knowledge may have a direct positive effect on developing breakthrough innovations.

We choose to investigate these issues in the context of nanotechnology. Nanotechnology presents an ideal setting for this research. The paper's focus on firm-originated knowledge requires that firms should generate significant knowledge in the focal area. The field of nanotechnology shows that firms have indeed contributed actively and importantly to the advancement of nanotechnology. For instance, the development of the Scanning Tunneling Microscopy (STM) came from IBM in early 1980s. NEC, a Japanese company, discovered carbon nanotubes (CNT) in 1990s. The empirical corroboration of our predictions will utilize the U.S. nanotechnology patents filed with the United States Patent and Trademark Office (USPTO) between 1978 and 2004 to examine how firm-originated knowledge affects the generation of technological breakthroughs. In the empirical analysis, we found supports for our hypotheses.

THEORY AND HYPOTHESIS

Firm-originated Knowledge and Breakthrough Innovations

Firms have attained technological progress through responding to downstream market needs (Rosenberg, 1974) or performed even basic research by themselves (Rosenberg, 1990) and thus, possess a significant amount of knowledge about current technology and opportunities for improvement (Nelson and Winter, 1982). For example, in the field of nanotechnology, firms own 80 percent of granted patents (Zucker et al., 2007). Further, firms regard firm-possessed information as the predominant source for industrial research and development (Cohen, Nelson, and Walsh, 2002). However, the role of this large body of firm technological knowledge in driving innovations is puzzling because superiority of university technology that has theoretically guided and structured following technological development (Mansfield, 1990; Rosenberg, 1990; Zucker, Darby, and Armstrong, 2002; Fleming and Sorenson, 2004) implies that firm-developed technology has seemed to be a beneficiary of university technology rather than a generator of breakthrough innovations. To understand the role of firm-developed technology on technology development, we examine firm-originated knowledge that is incorporated in innovations.

Developing the argument on the role of firm-originated knowledge requires elaborating the definition of novel knowledge generation and a breakthrough innovation. We begin with a widely consented proposition that novel knowledge generation is the process of newly recombining existing knowledge components (Schumpeter, 1939; Nelson and Winter, 1982; Henderson and Clark, 1990; Weitzman, 1998; Fleming, 2001). The recombination can be initiated by searching for external prior-knowledge (Nelson and Winter, 1982; Rosenberg and Neckar, 2001) and processed by merging diffused knowledge from others (Jaffe, 1986; Cohen and Levinthal, 1990; Griliches, 1992). External knowledge may be embedded by a firm's intentional search (Rosenkopf and Nerkar, 2001) as well as by unrecognized knowledge diffusions invoked by serendipitous hearing about existing knowledge and opportunities for its use (Hansen, 1999). Thus, embedded knowledge, regardless of whether the result of intentional search or by non-inquired hearing, represents prior-knowledge that is recombined to an innovation and thereby, can be trails that show how a recombinant innovation uses prior-knowledge as components.

The literature defines recombined components for innovations as “conceptual or physical materials,” such as routines or technologies (Nelson and Winter, 1982); “old knowledge,” such as existing cultivated plant varieties (Weitzman, 1998); pre-existing “elements,” such as materials in periodic tables and conditions—temperature and pressure (Romer, 1994); and “constituents of innovation,” such as Schumpeterian “factors” (Schumpeter, 1939; Fleming, 2001). Along the lines of this literature, in this paper, “knowledge components” denote the existing knowledge that was generated by prior innovations and then composes following innovations. Accordingly, firm-originated knowledge most likely reflects the extent to which knowledge components from firms’ prior innovations are incorporated into a focal innovation. From the perspective of evolutionary theory, the innovation that serves as inputs for future innovations are substantive in technology development. Thus, an innovation can be regarded as successful when other researchers recognize and build on the innovation (Simonton, 1999; Fleming, Mingo, and Chen, 2007). Following many researchers (Trajtenberg, 1990; Ahuja and Lampert, 2001; Zucker, Darby, and Armstrong, 2002; Singh and Fleming, 2010), we define a breakthrough innovation as a highly valuable innovation that has impacts on many subsequent innovations. Therefore, in this paper, a breakthrough innovation is an innovation-specific measure regarding the degree of impacts on future technology development.

For two reasons, we expect that the likelihood of new recombination decreases with increasing firm-originated knowledge. First, while university knowledge is likely to be fundamental, firm knowledge is related to applied and downstream technology. Fundamental scientific knowledge from university research can be a foundation for following technological innovations (Bush, 1945; Rosenberg, 1974) and thus guide and structure the direction of technology development processes. Hence, firms who adopt university-generated technology may reduce the uncertainty inherent in technology development (Nelson, 1962; Fleming and Sorenson, 2004). Moreover, because university technology tends to offer knowledge of why the technology works (von Hippel, 1994), by incorporating technological knowledge from university, firms can broaden the application of their innovations. On the contrary, firms produce, in general, applied technologies that offer less room to be newly recombined in subsequent innovations. That is because firms have elaborated and refined existing technologies and rearranged them within the boundary of pre-defined technological frameworks (Henderson and Clark, 1990), and thus firms have much likely exploited potential cases of recombination within the specific range of technologies (Kim and Kogut, 1996).

Further, technology development by firms within related industries may proceed along a "trajectory," as if moving toward some physical limits (Nelson and Winter, 1977; Dosi, 1982; Cohen, 2010). This trajectory is related to firms' technological development efforts that tend to be concentrated on a limited number of distinct, identifiable problems (Rosenberg, 1969; Nelson and Winter, 1977). Given that problem-solving along the trajectory may produce knowledge that answers to specific requirements highlighted in the related industries, by incorporating firm-originated knowledge, the resulting innovations will tend to be bounded by the trajectory that converges to the industries' consented technological interests. Therefore, along with firms' efforts to refine and elaborate applied technology in the specific technological area, the bounded trajectory may accelerate the exhaustion of feasible cases of new recombination. Hence, intense firm-originated knowledge will result in innovations with less novel recombination of knowledge.

Second, firm technology tends to be context-dependent because firms usually develop technologies for the purpose of specific application (Arora and Gambardella, 1994). This implies that firm-originated knowledge conveys an "encapsulation" of knowledge components that includes salient components as well as underlying contexts (Simon, 1996). To utilize this encapsulation or some parts of it as a component for new recombination, the inventors who adopt firm-originated knowledge should not only capture the salient components but also understand the underlying contexts. That is, inventors who receive the context-dependent knowledge need to understand the larger system that integrates focal and context knowledge (Hansen, 1999). For example, when Altairs Nanotechnologies, Inc. developed a nano-titanate material to improve the performance of rechargeable batteries such as lithium-ion batteries, Altairs needed to consolidate its technology into the prior ion battery system. To render its new material viable, Altairs should not only develop the related material but also study the system of the lithium-ion battery. While replacing graphite in conventional ion batteries with the new nano-titanate material, Altairs had to test the new combination of the ion battery and the new material repeatedly in a real battery cell through a multi-year research program. Finally, while Altair started without battery cell technology, due to the need for expertise on the battery system, it built its own battery development team through an acquisition (Altairnano, 2005).

With more firm-originated knowledge, inventors may be required to better understand underlying contexts of the firm specific knowledge. Known that inventors are bounded by limited cognitive abilities (March and Simon, 1958), their understanding of underlying contexts may lack expertise. This low expertise on knowledge components may hinder the inventors from rearranging the knowledge in novel ways (Fleming, 2002). Therefore, by incorporating context-dependent knowledge from firms, innovations will reduce the likelihood of new recombination.

The previous arguments explain the decreasing effect of firm-originated knowledge on new recombination. We expect that this reduced generation of novel recombination may decrease the likelihood of breakthrough innovations. As reducing novel recombination, focal innovations may re-use existing combinations of prior knowledge components. Innovations based on the redundant use of existing combinations are not likely useful for subsequent innovations (Kim and Kogut, 1996; Fleming, 2001). Furthermore, this exploitation of existing combinations will likely lead to reduced exploration of undefined novel recombination. This reduced exploration decreases the variance of outcome performance (March, 1991). Thus, by assuming a distribution of innovations with the degree of usefulness, we suggest that decreased novel recombination in an innovation will result in smaller variances—that is, fewer outliers in the usefulness of the innovation. The reductions in both tails in the distribution indicate fewer breakthrough outcomes.

Further, increase in embedding firm-originated knowledge may reflect that the resulting innovation is a specific applied technology to solve underlying problems in following a technology-development trajectory (Nelson and Winter, 1977; Dosi, 1982). As firms that try to solve bottlenecks and get rid of obstacles on the trajectory pursue a specific applied technology (Henderson and Clark, 1990), the achieved applied technology may confine its future usage to the specific application and thus reduce the usefulness of the innovation for broad areas. Given that with this applied technology, firms have been interested in appropriating their innovations, firm-originated knowledge may be already appropriated by the owners of the knowledge. Thus, the resulting applied technology that embeds firm-originated knowledge may limit its own appropriability as well as future adopters potential appropriability (Teece, 1986). Therefore, the innovations that depend on firm-originated knowledge to produce specific applications may decrease the likelihood of being breakthrough innovations.

Taken together, firm-originated knowledge that carry the components of applied and context-dependent technology lead focal innovations to generate less novel recombination and reduce future usages and appropriability, decreasing the innovation's usefulness for subsequent innovations. We summarize the discussion in the following hypothesis.

Hypothesis 1a: A breakthrough innovation is a negative function of firm-originated knowledge that is embedded in the innovation.

A significant portion of arguments for Hypothesis 1a depends on the role of novel recombination. This implies that novel recombination partially mediates the effect of firm-originated knowledge on breakthrough innovations. The increase in firm-originated knowledge reduces the likelihood of new recombination that affects positively the generation of breakthrough innovations and thus, decreases the likelihood of breakthrough innovations. We therefore hypothesize:

Hypothesis 1b: The effect of firm-originated knowledge on a breakthrough innovation is partially mediated by novel recombination.

Diversity of Firm-originated Knowledge and Breakthrough Innovations

Firm-originated knowledge may come from a single knowledge source or multiple knowledge sources. The multiple knowledge sources may increase diversity of firm-originated knowledge. Specifically, when the sources of firm-originated knowledge are not concentrated to a few number of homogeneous firms, firm-originated knowledge may carry diverse knowledge components that would be recombined in subsequent innovations. While firm-originated knowledge negatively affects the likelihood of breakthrough innovations, we expect that diversity of firm-originated knowledge most likely engenders breakthrough outcomes. There are three reasons for this expectation: introducing novel recombination, increasing potential audiences, and reducing the risk of intellectual lock-in.

First, the knowledge from diverse firms is likely to include novel components that have not yet been introduced to or considered for the specific technology domain to which the adopter of firm-originate knowledge belong. For instance, in developing a breakthrough nanotechnology of graphene, a two-dimensional carbon structure, nanotechnology researchers in the Manchester group used the "Scotch Tape" technique (i.e., micromechanical cleavage technique), a random and novel approach from the perspective of nanotechnology, in order to isolate graphene (Geim, 2009). Diverse sources can provide unexpected knowledge components that critically and serendipitously contribute to an innovation. This heterogeneous component can increase novelty of rearrangements and thus this arrangement can be valuable far more than the configuration without this random component (cf. Romer, 1994). This effect is parallel to the impact of diverse research portfolio of a society on technological progress of the society on the whole in Acemoglu (2010) in that diversity enables the input of unexpected components that the relatively homogeneous major components cannot come up with (cf. Hong and Page, 2004). Hence, recombination using diverse knowledge components may outperform other recombination of homogenous knowledge components in generating novelty.

Further, even if the knowledge from diverse sources do not include a random and novel component, diverse firm-originated knowledge may increase the likelihood of novelty generation. With the rearrangement of previously used components, new recombination can be achieved, resulting in breakthrough innovations (Henderson and Clark, 1990). Diverse firm-originated knowledge facilitate this process because recombining diverse inputs will produce hybrids recombination (Weitzman, 1998). The hybrid recombination is more likely to generate new recombination than homogeneous recombination. The image of this hybrid recombination depends on Griliches's (1957) idea that hybrid corn produces strong breeds as it cross-inbreeds along the multiple generations of corn seeds. For instance, the inception of nanotechnology was based on this Grilichesian method to produce innovations (Darby and Zucker, 2003). The scanning tunneling microscope (STM) that enables nanotechnology researchers to obtain atomic-scale images and to manipulate individual atoms on the surfaces of material was the breakthrough innovation that recombined diverse technologies including scanning tip, scanner, piezoelectric controlled scanner, voltage and current control, and vibration control. The implication is that diversity of firm-originated knowledge may facilitate generating hybrid recombinant knowledge, leading to new recombination. For these reasons—the introduction of new components and hybrid ideas—diversity of firm-originated knowledge will increase new recombination. Along the similar argument in Hypothesis 1, the increased new recombination will lead to breakthrough outcomes.

Second, embedding diverse firm-originated knowledge is related to increasing potential users of the focal innovations because the focal innovation is based on diverse knowledge sources. Diverse firm-originated knowledge implies that the focal innovation may be embedded in diverse applied technologies and thus connected to many potential audiences (Kaplan and Vakili, 2014). As potential audiences that are involved in subsequent innovations will draw on the focal innovation, the focal innovation can increase its usefulness for subsequent innovations. Third, innovations intrinsically have technological uncertainty and thus, it can be critical to resolve this uncertainty for firms to make their innovations successful (Rosenberg, 1974). If an innovation concentrates on a few knowledge sources, the technological uncertainty of the innovation may increase as the concentration may induce an intellectual lock-in (Teece, 1986; Kaplan and Vakili 2014). In a changing technological environment, the intellectual lock-in to specific applied technology may reduce the value of the focal innovation for future technology development. Consequently, diversity of firm-originated knowledge can increase potential audiences for the focal innovation and mitigate technological uncertainty induced by intellectual lock-in hence, increase the likelihood of breakthrough innovations. Hence, we hypothesize the following:

Hypothesis 2a: A breakthrough innovation is a positive function of diversity of firm-originated knowledge that is embedded in the innovation.

Likewise Hypothesis 1a, the argument for Hypothesis 2a partially depends on new recombination, which mediates the positive effect of diversity of firm-originated knowledge on breakthrough innovations. We therefore hypothesize:

Hypothesis 2b: The effect of diversity of firm-originated knowledge on a breakthrough innovation is partially mediated by novel recombination.

METHODS

Sample

We identified 3,006 nanotechnology patents filed in the U.S., from 1978 to 2004, using the USPTO-entitled patents assigned to the Class 977 (Nanotechnology). Since the U.S. patents or pre-grant publications can be classified into 977 only as cross-references or secondary classifications (USPTO Classification order 1850, 2005), the Class 977 helps us to identify all patented nanotechnology research across all industry fields (e.g., semiconductor, material engineering, biotechnology, cosmetics, and other industries).

Our data construction also identified: (1) nanotechnology patents that are cited by any of these 3,006 nanotechnology patents (backward citations); (2) 11,095 subclass pairs under Class 977; and (3) the number of citations made by 2010 to these nanotechnology patents (forward citations). For the analysis, we used patents applied before 2005 and granted until 2010 because the grant date usually lags behind the application date by several years. Our variables are built on the patent application date because the event of embedding prior-knowledge can be measured more accurately by application date.

Dependent Variables

We utilized two measures of outcomes to test our hypotheses on the impact of firm-originated knowledge: breakthrough innovation and new recombination.

Breakthrough Innovation The patent literature has established forward citations as an indicator of economic, social, and technological success of the patented technology (e.g., Trajtenberg, 1990; Harhoff, 1999; Fleming, 2001; Zucker et al., 2003; Fleming, Mingo, and Chen, 2010). Following this convention, we measured breakthrough innovations using forward citations. Specifically, we first generated the citation distribution of the entire population of U.S. patents (about 3.9 million) granted during 1976–2010. To account for differences in the citation hazard due to timing and technology, we regressed the number of forward citations on patent class, application year, and grant year to recover the residuals. This adjustment allowed us to compare the number of forward citations across patents that were applied for and granted in the same year and in the same technology class. We then computed the z-scores based on these normalized forward citations. Finally, we defined a breakthrough innovation as the patent belonging to the top 5% of the citation distribution (Singh and Fleming, 2010) and assigned '1' to the measure for these patents and '0' to others.

New Recombination Because subclasses allow us to examine fine-grained classifications of nanotechnology (Trajtenberg, Henderson, and Jaffe, 1997; Thompson and Fox-Kean, 2005), researchers increasingly focus on the subclass classification of patents to examine technology transfer, technology recombination, and patent scope (Lerner, 1994; Fleming, 2001; Thompson and Fox-Kean, 2005; Fleming and Sorenson, 2004; Fleming, Mingo, and Chen, 2007). A first-ever recombination of two subclasses can be considered as inventing a new aspect of corresponding technology (Fleming, 2001; Fleming and Sorenson, 2004; Fleming, Mingo, and Chen, 2007). Following this convention, we operationalized novelty generation by measuring the new recombination of subclasses that a nanotechnology patent establishes for the first time for the entire population of patents as well as for the field of nanotechnology. Hence, this measure allowed us to capture the first-time introduction of new recombination of subclasses to the field of nanotechnology. For each nanotechnology patent, we constructed a dummy variable that indicates if the patent incorporates new recombination.

Independent Variables

Firm-originated Knowledge We used patent backward citations to measure firm-originated knowledge (Mowery, Oxley, and Silverman, 1996; Gomes-Casseres, Hagedoorn, and Jaffe, 2006). Specifically, we constructed the measure for each patent that is the number of backward citations made to firm nanotechnology.

Diversity of Firm-originated Knowledge We identified diversity of firm-originated knowledge based on how concentrated the sources of the knowledge for an innovation are. We computed diversity using the Herfindahl index.

$$\text{Diversity of firm originated knoweldg} = 1 - \sum_{i=1}^{n} \mathrm{S}_{\mathrm{i}}^{2}$$

S_i is the share of firm i in the sources of knowledge for a patent. If all backward citations to firms belonged to only one firm, the diversity will be zero. On the contrary, if backward citations to firms are not concentrated on the small number of firms, the diversity is close to one. Therefore, this measure ranges from zero to one. We assumed diversity to be zero with zero backward citations to firms. We checked robustness by using zero backward citations to firms as missing values. We calculated the diversity of university-originated knowledge for robustness check in the same manner.

Control Variables

Citation to University Patent We controlled the number of backward citations made to university nanotechnology patents to capture the effect of university-originated knowledge. The patent citation measure cannot capture the entirety of university-originated knowledge because universities favor the publication of research findings in academic journals over the application of patents (Roach and Cohen, 2012). However, we can—at least for knowledge that universities filed as patents—control the effect of prior arts from universities. Given that university-originated knowledge affects positively the following innovations (Rosenberg, 1990; Fleming and Sorensen, 2004), it may be positively correlated with breakthrough innovations.

All Backward Citations To isolate the effect of backward citations to firms, we include the total number of backward citations.

Non-patent References The technology associated with each patent has a different degree of basicness or application. Because more basic technology-based patents may have more non-patent references, and more basic or less applied technology may, by nature, receive more citations, we included the number of non-patent references as a control variable. Hence, we controlled for this effect by including the number of non-patent references. We expect that non-patent references capture another confounding effect of academic knowledge on future citations because this proxy for the usage of academic knowledge is also highly correlated with future citation measures (Fleming and Sorenson, 2004; Ahuja and Katila, 2004).

Claims We included the number of claims to control for the effect of patent claims on the dependent variables. In particular, we expect that patents with more claims are likely to command more forward citations. Patent claims reflect the technological originality or the coverage of protection and, hence, may be positively correlated with the forward citations of a patent.

University patent We included the dummy for patents assigned to universities to control for the effects of university research in generating breakthrough innovations.

Year Fixed Effects We included application year dummies to capture the temporal effects in the development of nanotechnology.

Organization Fixed Effects We included the organization fixed effects to account for heterogeneity in organizational capabilities.

Estimation Methodology

We estimated logit models with the dependent variables indicating whether each patent belonged to the top 5% in the forward citation distribution, controlling for year and organization fixed effects. We report heteroskedasticity-robust standard errors. We tested the mediator Hypotheses 1b and 2b with procedures suggested by Baron and Kenny (1996) and Singh and Fleming (2010). Specifically, to test mediating effects, for the first step, we estimated logit models with new recombination as the dependent variable to show that firm-oriented knowledge/diversity of firm-oriented knowledge are negatively/positively associated with new recombination; the second step checked that the mediator, new combination, is positively associated with the likelihood of breakthrough innovation; for the third step, we examined the models, including both firm-originated knowledge/diversity of firm-oriented knowledge and new recombination as the independent variables.

RESULTS

Summary statistics of all variables and the matrix of correlations among them are reported in Table 1. Tables 2, 3, and 4 present the regression results. Model 2-1, 3-1, and 4-1 provides a baseline model with only control variables.

The analysis reported in Models 2-2, 2-3, 2-4, and 2-5 demonstrates that the patents with more firm-originated knowledge are less likely to become breakthrough innovations. Model 2-2 supports Hypothesis 1a: the term of firm-originated knowledge indicates a negative and significant effect on breakthrough innovations. We found support for Hypothesis 1b from Models 2-3, 2-4, and 2-5. First, in Model 2-3, the term of firm-originated knowledge indicates a negative and significant effect on new recombination. Second, in the regression not including firm-originated knowledge, new recombination is positively associated with the likelihood of breakthroughs. Third, in Model 2-5, the regression includes both terms of firm-originated knowledge and new recombination, indicating a positive and significant effect of new recombination and a negative and significant effect of firm-originated knowledge on breakthrough innovation. The results indicate that new recombination partially mediate the effect of firm-originated knowledge on breakthrough innovation.[1]

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[1] Specifically, we first added to Model 2-5 in Table 2 the variable new recombination. The coefficient of this variable was positive and significant ($\beta = 0.668$, $p<0.01$) while that of firm-originated knowledge remained negative

Next, we examined how diversity of firm-originated knowledge affects the likelihood of breakthrough innovations. Models 2-6 and 2-8 support Hypothesis 2a: the term of diversity of firm-originated knowledge indicated a positive and significant effect on breakthrough innovations. Models 2-7 and 2-8 support Hypothesis 2b: the term of diversity of firm-originated knowledge indicated a positive and significant effect on new recombination and a positive and significant effect on breakthrough innovation with inclusion of the mediator, new recombination.[2]

Our results have so far showed that diversity of firm-originated knowledge increases breakthrough innovations. To resolve the concern that the result may come not from the effect of diverse firm-originated knowledge but from the positive effect of diversity—regardless of knowledge sources—which has been established well in literature, we tested robustness with diversity of university-originated knowledge, isolating the effect of diversity of firm-originated knowledge from that of university-originated knowledge. As shown in Models 2-9 and 2-10, the term of diversity of university-originated knowledge indicated a negative and significant effect on breakthrough innovations. The result supports Hypothesis 2a and 2b, demonstrating the distinguished effect of diverse firm-originated knowledge from diverse university-originated knowledge.

Robustness Check

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and significant ($\beta = -0.041$, $p<0.10$). We then compared this estimate on firm-originated knowledge with that in Model 2-2 ($\beta = -0.047$, $p<0.05$) using the two-sample t-test for comparing two means. The test strongly rejected the null hypothesis of coefficient equality ($t = -8.944$, $p<0.01$).

[2] We repeated the same procedure for diversity of firm-originated knowledge. In Model 2-8, the coefficient on new recombination was also positive and significant ($\beta = 0.646$, $p<0.01$) while that of diversity of firm-originated knowledge remained positive ($\beta = 0.489$, $p<0.05$). We then compared this estimate on diversity of firm-originated knowledge with that in Model 2-6 ($\beta = 0.515$, $p<0.05$) using the two-sample t-test for comparing two means. The two-sample t-test again rejected the null hypothesis of coefficient equality ($t = 1.824$, $p<0.01$).

Because there is a nontrivial correlation (0.65) between firm-originated knowledge and citation to university patents, we estimated the same model as Model 2-2 without the control variable of citation to university patents. The result (unreported) indicates that firm-originated knowledge have a negative and significant effect on breakthrough innovation, and thus the estimated effects in our regressions are not due to the collinearity between them. Also, to check the multicollinearity, we carried out a variance influence factor (VIF) analysis after regression (Cohen et al, 2003). The results indicate that the values of VIF are all under 5. Hence, the variables are not linear combinations of other variables.

In Table 3, we performed the regressions with alternative citation-related measures that excluded examiner-added citations. Specifically, for the variables of firm-originated knowledge, citation to universities, and all backward citations, we recalculated the number of citations by subtracting examiner-added citations. The results are robust for the effect of firm-originated knowledge and diversity of firm-originated knowledge on the likelihood of technological breakthroughs. In particular, with these alternative measures, Hypothesis 1b was partially supported in Models 3-3 and 3-7: the term of firm-originated knowledge that excluded examiner-added citations indicates a negative but insignificant effect on the likelihood of new recombination. This presents that the mediating effect of new recombination is weakened when we used firm-originated knowledge that excluded examiner-added citations as the independent variable.

We also employed same models without organization fixed effects in Table 4. The results were generally robust except that the effect of diversity of firm-originated knowledge on new recombination lacked significance, though the sign was consistent with the prediction. This result shows that the organization effect varies the effect of diversity of firm-originated knowledge on new recombination.

DISCUSSION AND CONCLUSION

The purpose of this paper is to examine the effect of firm-originated knowledge on breakthrough innovations. Our results reveal that firm-originated knowledge contributes to the development of breakthrough innovations when inputted from diverse firms. Specifically, by incorporating firm-originated knowledge, firms decrease the possibility that resulting innovations become breakthroughs outcomes, whereas by incorporating diverse firm-originated knowledge, firms increase the possibility of developing breakthrough innovations; and the novelty generation partially mediates both of these effects. Given that firm-originated knowledge is generally considered as applied and downstream-oriented, context-dependent, progressing along a natural trajectory, and with a view to an appropriation, by incorporating more firm-originated, the innovations may reduce novelty creation, general usages, and appropriability, leading to reducing the probability of being breakthroughs. On the contrary, by embedding diverse firm-originated knowledge, innovations will increase the probability of introducing new components and hybrid recombination. Thus, the innovations will become breakthrough innovations through novelty generation. Further, the benefit of potential various audiences and the low risk of intellectual lock-in, which are the benefits of diverse knowledge sources, may contribute to the direct positive effect of diverse firm-originated knowledge on breakthrough innovations.

This study is not without limitations. First, as noted above, our analysis depends on patent data. All innovations may not be applied to patent filing. This may be a fundamental limitation because the study of knowledge sources has been almost-exclusive relied on paper trails such as patent citations, which, by definition, can only capture codified knowledge, thereby failing to reflect transfers of knowledge through inter-organizational ties, consulting or informal meetings (Roach and Cohen, 2013). Though we have made efforts to mitigate this problem by studying a field where patenting is important, future study could benefit from exploring more comprehensive coverage of the firm-originated knowledge including tacit or non-codified knowledge. Second, patent citations may not indicate that inventors knew about and intentionally used the specific knowledge sources (Alcacer and Gittelman, 2006). Nevertheless, our view that patent citations enable us to trace prior-knowledge that was embedded in innovations mitigates this concern because, by using backward citations, we pursue the sources of prior-knowledge—whether the sources are firm and how diverse the sources are—rather than inventors' recognition of the cited patents. That is, if examiners would add backward citations, it could help us to identify the sources of knowledge that inventors forgot to report or do not recognize as priory-arts. However, to be parsimonious, we eliminated the citations made by examiners and rebuilt alternative measures for the citation-related variables: the number of backward citations without examiner-added citations. The result shows robustness. Third, considerable unobserved factors may exist across organizations in choosing knowledge from others and thus intervene to generate innovative outcomes. To minimize this concern, we incorporated organization fixed-effects. This approach may address the unobserved time-invariant heterogeneities across organizations. Nevertheless, we acknowledge that due to a lack of data, the inability to fully address time-variant organization heterogeneity is clearly a limitation.

We hope that the paper offers two contributions to extending the literature on knowledge and innovations by demonstrating firm-oriented knowledge as the antecedents of breakthrough innovations. First, the paper identifies a mechanism by which firm-originated knowledge becomes critical to generating breakthrough innovations. While firm-originated knowledge, in general, seems to be not superior in driving highly valuable innovations, we suggest that by incorporating diverse firm-originated knowledge into an innovation, firms can enhance the value of their innovations and thus increase the likelihood of generating breakthrough innovations.

Second, we extend the well-accepted claim that diversity contributes to produce a highly valuable outcome by generating great variations for alternatives and selecting the best solution among the alternatives. That is, the claims mean that diverse inputs increase a pool for a selection and some of inputs not selected may perish. We submit evidence that an outcome that consists of diverse knowledge components may outperform. By examining diverse firm-originated knowledge that was embedded in an innovation, we demonstrate that the diversity that persists in outcomes affects the value of the innovation. Our finding offers to literature on diversity a mechanism through which diversity plays a significant role in producing breakthrough innovations.

From the managerial standpoint, our findings have an implication for firms that use firm-originated knowledge to develop an innovation. As firm-originated knowledge may exert dual influences—i.e., increasing or decreasing the likelihood of breakthroughs—on the resulting innovation. The finding emphasize that when an innovation embeds firm-originated knowledge, it is critical for firms to avoid concentrating on a few knowledge sources and thus free from intellectual lock-in. Hence, firms that incorporate firm-originated knowledge into their innovations should recombine diverse knowledge to achieve breakthrough innovations.

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Table 1 Summary Statistics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Breakthrough innovation										
(2) Firm-originated knowledge	0.009									
(3) Citation to universities	0.005	0.652								
(4) Diversity of Firm-originated knowledge	0.055	0.236	0.217							
(5) Diversity of university-originated knowledge	-0.027	0.036	0.000	0.128						
(6) New recombination	0.074	-0.051	-0.019	-0.034	-0.012					
(7) All backward citation	0.038	0.510	0.560	0.400	0.087	-0.016				
(8) Non patent reference	0.034	0.281	0.509	0.199	0.032	0.001	0.622			
(9) Claims	0.103	0.025	0.069	0.107	-0.012	0.010	0.140	0.115		
(10) University	0.040	-0.038	0.090	-0.047	-0.118	0.043	-0.037	0.141	0.073	
Obs	5401	5401	5401	5401	5401	5401	5401	5401	5401	5401
Mean	0.143	2.331	0.889	0.539	0.591	0.285	13.355	13.850	20.974	0.202
Std. Dev.	0.350	6.426	2.716	0.337	0.429	0.452	26.350	31.538	17.476	0.402
Min	0	0	0	0	0	0	0	0	0	0
Max	1	95	45	1	1	1	371	436	296	1

Note: All correlation coefficients above 0.03 or below -0.03 are significant at 5%.

Table 2 Regression Analysis of Breakthrough Innovations on Firm-originated Knowledge

	(2-1) Breakthroughs	(2-2) Breakthroughs	(2-3) New Recombination	(2-4) Breakthroughs	(2-5) Breakthroughs
Firm-originated knowledge		-0.047**	-0.054*		-0.041*
		(0.021)	(0.028)		(0.021)
New recombination				0.731***	0.668***
				(0.240)	(0.244)
Citation to universities	-0.041	0.012	-0.070	-0.031	0.014
	(0.038)	(0.044)	(0.080)	(0.039)	(0.044)
All backward citation	-0.000	0.005	0.020	-0.002	0.003
	(0.005)	(0.005)	(0.020)	(0.005)	(0.005)
Non patent reference	0.001	-0.001	-0.004	0.001	-0.001
	(0.003)	(0.004)	(0.006)	(0.003)	(0.004)
Claims	0.017***	0.016***	0.001	0.016***	0.016***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
University patent	1.597	1.608	1.002	1.560	1.573
	(1.134)	(1.145)	(1.331)	(1.133)	(1.144)
_cons	-7.124***	-6.947***	1.853	-7.818***	-7.603***
	(1.187)	(1.184)	(1.148)	(1.212)	(1.211)
Year fixed effect	Included	Included	Included	Included	Included
Organization fixed effect	Included	Included	Included	Included	Included
Log-likelihood	-906.626	-902.933	-533.089	-901.872	-899.095
N	1960	1960	1472	1960	1960

* p<0.10 ** p<0.05 *** p<0.01

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Note: Robust standard errors in parentheses. To show that new recombination partially mediate the effect of firm-originated knowledge on technological breakthroughs we first added to Model 2-5 in Table 2 the variable new recombination. The coefficient of this variable was positive and significant (β = 0.668, p<0.01) while that of firm-originated knowledge remained negative and significant (β = -0.041, p<0.10). We then compared this estimate on firm-originated knowledge with that in Model 2-2 (β = -0.047, p<0.05) using the two-sample t-test for comparing two means. The test strongly rejected the null hypothesis of coefficient equality (t = -8.944, p<0.01).

Table 2 Regression Analysis of Breakthrough Innovations on Firm-originated Knowledge (continued)

	(2-6) Breakthroughs	(2-7) New Recombination	(2-8) Breakthroughs	(2-9) Breakthroughs	(2-10) Breakthroughs
Firm-originated knowledge	-0.048**	-0.053*	-0.043*	-0.049**	-0.050**
	(0.023)	(0.028)	(0.023)	(0.021)	(0.023)
New recombination			0.646***		
			(0.245)		
Diversity of firm-originated knowledge	0.515**	0.627**	0.489**		0.545**
	(0.225)	(0.305)	(0.225)		(0.227)
Diversity of university-originated knowledge				-0.442***	-0.459***
				(0.150)	(0.151)
Citation to universities	0.016	-0.069	0.018	0.003	0.007
	(0.043)	(0.076)	(0.043)	(0.044)	(0.044)
All backward citation	0.001	0.015	-0.000	0.006	0.002
	(0.005)	(0.019)	(0.005)	(0.005)	(0.005)
Non patent reference	-0.001	-0.003	-0.000	-0.001	-0.001
	(0.004)	(0.006)	(0.004)	(0.004)	(0.003)
Claims	0.016***	0.002	0.016***	0.016***	0.016***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
University patent	1.507	0.789	1.483	1.401	1.297
	(1.170)	(1.323)	(1.169)	(1.125)	(1.155)
_cons	-7.234***	1.725	-7.859***	-6.554***	-6.851***
	(1.228)	(1.143)	(1.252)	(1.175)	(1.224)
Year fixed effect	Included	Included	Included	Included	Included
Organization fixed effect	Included	Included	Included	Included	Included
Log-likelihood	-900.306	-530.856	-896.731	-898.707	-895.786
N	1960	1472	1960	1960	1960

* p<0.10 ** p<0.05 *** p<0.01

Note: Robust standard errors in parentheses. To show that new recombination partially mediate the effect of firm-originated knowledge on technological breakthroughs we first added to Model 2-8 in Table 2 the variable new recombination. The coefficient of this variable was positive and significant (β = 0.649, p<0.01) while that of firm-originated knowledge remained negative and significant (β = -0.489, p<0.05). We then compared this estimate on firm-originated knowledge with that in Model 2-6 (β = -0.515, p<0.05) using the two-sample t-test for comparing two means. The test strongly rejected the null hypothesis of coefficient equality (t = -1.824, p<0.01).

Table 3 Regression Analysis of Breakthrough Innovations on Firm-originated Knowledge without examiner-added citation

	(3-1)	(3-2)	(3-3)	(3-4)	(3-5)
	Breakthroughs	Breakthroughs	New Recombination	Breakthroughs	Breakthroughs
Firm-originated knowledge		-0.042**	-0.037		-0.037*
		(0.021)	(0.024)		(0.021)
New recombination				0.722***	0.673***
				(0.240)	(0.243)
Citation to universities	-0.059	-0.007	-0.097	-0.048	-0.003
	(0.042)	(0.048)	(0.076)	(0.042)	(0.048)
All backward citation	0.001	0.005	0.013	-0.000	0.004
	(0.005)	(0.005)	(0.015)	(0.005)	(0.005)
Non patent reference	0.001	-0.001	-0.001	0.001	-0.001
	(0.003)	(0.004)	(0.006)	(0.003)	(0.004)
Claims	0.017***	0.017***	0.001	0.016***	0.016***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
University patent	1.603	1.617	1.006	1.567	1.583
	(1.135)	(1.144)	(1.338)	(1.134)	(1.143)
_cons	-7.163***	-6.982***	1.806	-7.843***	-7.638***
	(1.192)	(1.186)	(1.148)	(1.217)	(1.213)
Year fixed effect	Included	Included	Included	Included	Included
Organization fixed effect	Included	Included	Included	Included	Included
Log-likelihood	-906.285	-903.436	-535.192	-901.657	-899.515
N	1960	1960	1472	1960	1960

* p<0.10 ** p<0.05 *** p<0.01

Robust standard errors in parentheses.

Table 3 Regression Analysis of Breakthrough Innovations on Firm-originated Knowledge without examiner-added citation (continued)

	(3-6)	(3-7)	(3-8)	(3-9)	(3-10)
	Breakthroughs	New Recombination	Breakthroughs	Breakthroughs	Breakthroughs
Firm-originated knowledge	-0.043*	-0.035	-0.038*	-0.044**	-0.045**
	(0.022)	(0.024)	(0.022)	(0.022)	(0.023)
New recombination			0.650***		
			(0.244)		
Diversity of firm-originated knowledge	0.485**	0.677**	0.457**		0.513**
	(0.222)	(0.281)	(0.222)		(0.223)
Diversity of university-originated knowledge				-0.442***	-0.458***
				(0.149)	(0.151)
Citation to universities	-0.002	-0.101	0.001	-0.015	-0.010
	(0.048)	(0.072)	(0.048)	(0.049)	(0.048)
All backward citation	0.002	0.009	0.001	0.007	0.003
	(0.005)	(0.014)	(0.005)	(0.005)	(0.005)
Non patent reference	-0.000	-0.000	-0.000	-0.001	-0.000
	(0.004)	(0.005)	(0.004)	(0.004)	(0.004)
Claims	0.016***	0.002	0.016***	0.016***	0.016***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
University patent	1.523	0.778	1.500	1.408	1.311
	(1.169)	(1.325)	(1.168)	(1.124)	(1.154)
_cons	-7.247***	1.664	-7.870***	-6.583***	-6.857***
	(1.229)	(1.137)	(1.253)	(1.177)	(1.225)
Year fixed effect	Included	Included	Included	Included	Included
Organization fixed effect	Included	Included	Included	Included	Included
Log-likelihood	-901.024	-532.463	-897.383	-899.197	-896.517
N	1960	1472	1960	1960	1960

* p<0.10 ** p<0.05 *** p<0.01

Robust standard errors in parentheses.

Table 4 Regression Analysis of Breakthrough Innovations on Firm-originated Knowledge without Organization Fixed Effect

	(4-1)	(4-2)	(4-3)	(4-4)	(4-5)
	Breakthroughs	Breakthroughs	New Recombination	Breakthroughs	Breakthroughs
Firm-originated knowledge		-0.024***	-0.058***		-0.021**
		(0.009)	(0.019)		(0.009)
New recombination				0.510**	0.444**
				(0.202)	(0.202)
Citation to universities	0.054***	0.098***	-0.058	0.058***	0.096***
	(0.019)	(0.027)	(0.049)	(0.020)	(0.027)
All backward citation	0.002	0.004*	0.022	0.002	0.004*
	(0.002)	(0.002)	(0.016)	(0.002)	(0.002)
Non patent reference	0.002	0.001	-0.001	0.002	0.001
	(0.002)	(0.002)	(0.004)	(0.002)	(0.002)
Claims	0.013***	0.013***	-0.004	0.013***	0.013***
	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
University patent	0.327***	0.315***	-0.169	0.332***	0.322***
	(0.107)	(0.107)	(0.163)	(0.107)	(0.108)
_cons	-4.454***	-4.524***	2.377***	-4.937***	-4.931***
	(0.448)	(0.472)	(0.231)	(0.484)	(0.497)
Year fixed effect	Included	Included	Included	Included	Included
Organization fixed effect	No	No	No	No	No
Log-likelihood	-1368.920	-1365.511	-807.351	-1365.447	-1362.942
N	2999	2999	2930	2999	2999

* p<0.10 ** p<0.05 *** p<0.01

Robust standard errors in parentheses.

Table 4 Regression Analysis of Breakthrough Innovations on Firm-originated Knowledge without Organization Fixed Effect (continued)

	(4-6)	(4-7)	(4-8)	(4-9)	(4-10)
	Breakthroughs	New Recombination	Breakthroughs	Breakthroughs	Breakthroughs
Firm-originated knowledge	-0.025**	-0.057***	-0.021**	-0.024***	-0.025**
	(0.010)	(0.020)	(0.009)	(0.009)	(0.010)
New recombination			0.427**		
			(0.201)		
Diversity of firm-originated knowledge	0.437***	0.148	0.425***		0.468***
	(0.164)	(0.284)	(0.165)		(0.165)
Diversity of university-originated knowledge				-0.262**	-0.288**
				(0.113)	(0.115)
Citation to universities	0.100***	-0.057	0.098***	0.096***	0.098***
	(0.027)	(0.050)	(0.027)	(0.027)	(0.026)
All backward citation	0.002	0.021	0.002	0.005**	0.003
	(0.003)	(0.018)	(0.003)	(0.002)	(0.002)
Non patent reference	0.001	-0.000	0.001	0.001	0.001
	(0.002)	(0.004)	(0.002)	(0.002)	(0.002)
Claims	0.012***	-0.004	0.013***	0.013***	0.012***
	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)
University patent	0.335***	-0.166	0.341***	0.276**	0.294***
	(0.108)	(0.161)	(0.108)	(0.109)	(0.110)
_cons	-4.736***	2.311***	-5.123***	-4.361***	-4.570***
	(0.470)	(0.248)	(0.494)	(0.471)	(0.468)
Year fixed effect	Included	Included	Included	Included	Included
Organization fixed effect	No	No	No	No	No
Log-likelihood	-1362.002	-807.142	-1359.637	-1362.868	-1358.863
N	2999	2930	2999	2999	2999

* p<0.10 ** p<0.05 *** p<0.01

Robust standard errors in parentheses.