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A template for invention: Renewing & recycling knowledge components

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OLD TECHNOLOGIES AS TEMPLATES FOR NEW INVENTIONS

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INTRODUCTION

> *"The creation of any sort of novelty in art, science, or practical life – consists to a substantial extent of a recombination of conceptual and physical materials that were previously in existence"* (Nelson & Winter, 1982: 130).

Forming new combinations of existing technologies is a principal source of innovation (Galunic & Rodan, 1998; Schumpeter, 1947). These innovations require the creation of a link between the sometimes divergent needs of markets and technologies (Freeman, 1982 in Dougherty, 1992). Therefore, firms that attempt to innovate inevitably make combinatorial choices that are prone to failure. Given this risk, we investigate how combining components of existing technologies can generate impactful innovations. We differentiate between *recycling* and *renewing* technological components – both of which are processes that lead to the generation of new inventions. Recycling is when previously used components are recombined in a novel way or if one or more components are subtracted from the original combination. Renewal, on the other hand, is when a new component is introduced to an original combination or if it replaces one or more existing components.

We build on earlier work (Fleming, 2001, 2002; Henderson & Clark, 1990), to show that the reuse of existing components leads to inventions that are, on average, more valuable than when such components are combined for the first time. Next, we examine the different ways in which components can be reused to show that renewal leads to higher impact inventions than recycling. Two other factors also affect the impact of these inventions. The amount of time that elapses until components are reused has a negative impact, meaning that firms benefit from recombining components of recently developed technologies. Additionally, these inventions are more valuable when a firm is aware of, and is able to absorb external knowledge. These findings contribute to the recombination literature (Henderson & Clarck, 1990; Fleming, 2001), to the broad literature on search (Cyert & March, 1963), and to research that has explored the relationship between time, search, and innovation (Ahuja & Katila, 2002; Katila, 2001; Nerkar, 2003).

THEORY AND HYPOTHESES

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Because the recombination of components is fundamental to innovation (Basalla, 1988; Schumpeter, 1939), firms naturally exploit their combinative capabilities to create and respond to market and technological opportunities (Grant, 1996; Kogut & Zander, 1992, 1996; Zander & Kogut, 1995). Still, firms exhibit considerable variation in the extent to which they are able to exploit internal knowledge repositories (Katila & Ahuja, 2002; March, 1991). We argue that firms innovate more efficiently when they use their previous technologies as templates for new inventions because they are more familiar with these technologies' building blocks. When a firm is combining new components for the first time, it would need to experiment with various combinations, only some of which would be successful. This process, which is both costly and time-consuming, places the firm at a comparative disadvantage in the race to invention because of time compression diseconomies (Dierickx & Cool, 1989). Additionally, a firm is more familiar with the processes of re-using and refining components that have been used before. Past combinative experience presents firms with vital information regarding which combinations have failed previously, allowing them to avoid similar errors (Fleming, 2001). By contrast, this insight is unavailable when entirely new combinations are being developed, leading the firm to experiment. Inevitably, the outcome of experimentation is risky and uncertain, and this can hurt the output of innovation (March, 1991). As a final point, while 'beginner's luck' is not impossible – Biogen's blockbuster drug interferon beta-la for instance built on no internal patents (George, Kotha, & Zheng, 2008) – such stories are a consequence of positive selection bias. In general, "chance favours the connected mind" (Johnson, 2011) and these 'connections' are a consequence of experience and hard work. For these reasons, we hypothesize that:

Hypothesis 1: The impact of a firm's invention that reuses a combination from a previous invention is higher than that of inventions that strictly combine new components.

Recycled and renewed inventions both reuse combinations of components from previous inventions, but in the latter a new component is introduced. Based on this definition, the extent to which a firm is familiar with a combination is naturally less when the invention is arrived at through renewal. Whereas this may suggest that renewed inventions will attain a lower impact, a number of arguments lead us to believe that this is not the case. Although recombining the familiar can have "great competitive consequences" (Henderson & Clark, 1990), over time, a firm will exhaust all useful combinations (Fleming, 2001). Eventually, the potential for new recombinations along the same trajectory (i.e. using the some components) becomes increasingly more difficult, particularly when an industry approaches the technological frontier (Dosi, 1982, 1988). In such a situation, the probability of detecting novel combinations diminishes simply because there is less novelty to detect (Galunic & Rodan, 1998). As argued by Gatignon et al. (2002: 1105) "[t]hose innovations that build on existing competencies are positively associated with commercial success, particularly when they are incremental and/or they are associated with new competence acquisition". Fleming (2001: 120) makes a similar argument: "If semiconductor inventors restricted their usage to their original materials of aluminum and bipolar transistors, progress in the field would have halted long ago." Thus, we propose that while recombinations result in higher impact inventions than new combinations, adding some novel components to a familiar combination is likely to be beneficial. This leads to the following hypothesis:

Hypothesis 2: On average, renewed inventions have higher impact than recycled ones.

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Temporal lapse and external search

In the course of a firm's existence, it accumulates a large body of knowledge, information and insights surrounding its inventive activities. Having access to this body of prior knowledge is vital as it allows inventors to repeat techniques that have proved successful, and avoid combinations that have previously failed. Indeed, the reuse of old knowledge is generally assumed to be a more reliable endeavour (March, 1991) and is also less likely to incite competitive responses (Smith et al, 1991). The caveat is that organizations forget. In other words, important knowledge relating to a firm's inventive activities depletes over time (Argote, Beckman, & Epple, 1990). Since firms forget older knowledge, inventors that build on more recent experience are better able to avoid failure, and thus, generate new combinations more efficiently (Nerkar, 2003).

Apart from organizational memory, another factor that is influenced by time, and which influences the impact of the resulting inventions, is the ability to generate a useful combination. The entire premise of this paper is that old combinations can be reused to generate new inventions. However, if one were to only rely on a limited number of components then, over time, the potential for generating valuable combinations decreases (Kim & Kogut, 1996). For these reasons, we expect that the amount of time that elapses until a combination is reused would have a negative impact on the generated invention.

All else being equal, we expect temporal lapse to have a more negative effect on renewed inventions than on recycled inventions. Renewed inventions contain components that were never previously used by the firm. The integration of these components with existing combinations would require more experimentation, as there will be a certain degree of uncertainty about how they will interface with one another. We argued previously that inventors are less familiar with combinations in which new components are included. The lack of familiarity increases inventive risk and consequently, it also increases the chances of producing knowledge with more problems (Fleming, 2001). By contrast, because inventors are more familiar with the combination of components in recycled inventions, the inventive uncertainty in these processes are lowered. We therefore hypothesize:

> *Hypothesis 3: Increasing the amount time it takes to reuse a combination from a previous invention lowers the impact of these inventions. This effect is more pronounced for renewed inventions than for recycled ones.*

Previous work has shown that search scope has a positive linear effect on product innovation (Katila & Ahuja, 2002). Even when a firm's new invention entails re-using components, there is an advantage to scanning the external environment and absorbing relevant knowledge because "inventors can draw on others' knowledge and experience in addition to their own" (Fleming, 2001: 120). The absorption of external knowledge increases not only the number of problems that can be solved (Fleming & Sorenson, 2004), but also the number of solutions to each of these problems (March, 1991). Incorporating external knowledge sources and technologies in this way reduces the influence of competency traps and core rigidities (Leonard-Barton, 1992; Levinthal & March, 1993).

We expect external search to have a larger effect on recycled inventions than renewed inventions for a number of reasons. Recycled inventions are typically associated with deeper searches within the firm's knowledge base. Since external search mitigates the risks of excessive

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search depth, it is expected to improve the impact of recycled inventions. By contrast, renewed combinations already contain a novel component, making external search less needed for mitigating the risks associated with search depth. The inclusion of a new component to form a renewed invention also increases the cognitive strain on the inventors; which could be magnified by scanning the external environment for different sources of novel knowledge. Therefore we hypothesize that:

Hypothesis 4: The extent of external search that is conducted to reuse a combination from a previous invention increases the impact of these inventions. This effect is stronger for recycled inventions than for renewed ones.

DATA AND METHODS

We test our hypotheses using panel data from 83,786 patents assigned to 159 firms in the US semiconductor industry, spanning the period 1990-2004. US semiconductor firms have high invention rates as R&D is central to their day-to-day activities (Lahiri, 2010; Mathews & Cho, 1999; Park, Chen, & Gallagher, 2002). These firms rely on both internal and external sources of knowledge (Appleyard, 1996; West, 2002) and have high patenting rates, especially since the 1980s (Hall & Ziedonis, 2001; Stuart, 2000), making patent data an appropriate proxy for invention in this industry. Patent documents list technological classes and subclasses. The latter provide a granular identification of the technologies used and can meaningfully serve as proxies for technological components (Fleming, 2001; Fleming & Sorenson, 2001, 2004; Sorenson, Rivkin, & Fleming, 2006). Patent citations capture the flow of knowledge, or technological information, between patents (Hall, Jaffe, & Trajtenberg, 2001, 2005; Jaffe, Trajtenberg, & Henderson, 1993).

Variables

We measure our *dependent variable impact* as the number of forward citations that a patent receives, which is correlated with the invention's economic importance and expert evaluations of its value (Hall et al., 2005; Jaffe, Trajtenberg, & Romer, 2002).

Regarding our *explanatory variables* we "do not propose that inventors recombine patent subclasses directly, only that subclasses can be used to observe indirectly the process of recombinant search and learning" (122) so that these subclasses can be interpreted as proxies for the "basic building blocks of our technological community" (Fleming, 2001: 123). *Recombination* occurs when a patent contains at least two components that have appeared together in at least one of the firm's previous inventions (when there are multiple candidate reference patents, we pick the most recent one (Fleming, 2001)). *Recycled inventions* are those that maintain exactly the same components as in a previous invention or remove some components from a previous combination. In both cases, the firm is familiar with all the components in the invention (Fleming, 2001). *Renewed inventions* are those combinations that require the addition of at least one component to a familiar combination. The *temporal lapse* measures the number of years that has elapsed between the last time that a combination was used and the current invention. For virgin combinations, temporal lapse measures the number of years it takes a firm to re-create a combination that was developed in a competing firm. In 2,422 cases (=2.89%), we found that a combination was never previously used. To account for this, Temporal Lapse took a value of 0, but we included a dummy variable (entirely new invention) to

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capture these cases in our empirical models. Following other studies (Almeida & Phene, 2004; Katila, 2002), we construct *external search* by counting the prior art citations excluding self-citations.

We include a variety of *control variables* that have been shown to be relevant in the determination of firm outcomes. *Team size* (number of inventors) is positively correlated with forward citations (Singh & Fleming, 2010). *Technological maturity* is calculated as ratio of citations that the focal patent makes to prior art to the number of claims that it makes (Hoetker & Agarwal, 2007; Lanjouw & Schankerman, 2003). *Technological diversity* captures the range of technological classes to which a patent's backward citations belong *(e.g. Argyres & Silverman, 2004; Jaffe et al., 2002; Singh, 2008). Geographic dispersion* is measured as 1 minus the Herfindahl index of regional concentration, where a region is defined as a state in the US and a country elsewhere (e.g. Lahiri, 2010; Singh, 2008). We also include an annual patent count and measures for firm age and size, as well as year dummies.

Analysis

Following a Hausman (1978) specification test we use random effects negative binomial regressions. Correlation coefficients (not reported) were sufficiently low to not worry about multicollinearity. The mean value of the variable recombination is 0.69, which means that the majority of firm's patents (69%) recombine components that have been previously used together. Of these patents, approximately 32% are recycled and 68% renewed combinations.

RESULTS AND DISCUSSION

We find broad support for all our hypotheses. Our initial model (M1) which includes all inventions (recombinations and those that do not recombine previous components) shows support for hypotheses 1 and 2. Both recycled and renewed inventions have higher impact than the baseline of virgin combinations and the effect for the latter is significantly higher (0.110 > 0.025). The expected impact of patents that use any recombination types is about 8.8% higher than those which do not; in support of hypothesis 1. Note that we do not report the values for the control variables, which were all significant and in the expected direction.

Table 1 about here

The empirical analysis for our Model 2 (M2) only considers inventions which reuse existing combinations (i.e., Recombination = 1). Therefore, 58,011 patents belonging to 137 firms are retained in this analysis in which we compare the default of renewed inventions with recycled ones. The results for hypothesis 2 are formally confirmed. We find a significant and negative coefficient for recycled inventions ($b = -0.093$, $p < 0.001$). We further hypothesized that the time-lag between an invention and its predecessor would reduce the impact of recombinative inventions. Our findings support this and the interaction effect with recycled inventions is positive, showing the expected attenuation. Hypothesis 4 cannot be disproven because both the external search coefficient and the interaction with recycled inventions are positive and significant as hypothesised. Recycled inventions thus indeed benefit more from external search than renewed ones.

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How firms recombine old technological components to generate high impact innovations had not been enunciated in previous work. Our study finds 1) that both forms of recombination, namely recycling and renewing, yield higher impact inventions when compared to inventions in which components are combined for the first time, 2) that renewed inventions generally have higher impact and 3) that such inventions are more susceptible to the negative effects of temporal lapse and less susceptible to the positive effects of external search. These findings offer a number of insights that are relevant to managerial practice. Despite significant attention to thinking outside the box, inventing inside the box generates higher impact (Boyd & Goldenberg, 2013a, b). We also showed that while prior experience is important, there is a tendency for organizations to forget experiences that were accumulated in the distant past, and this negatively influences innovation. This finding emphasizes the importance of investing in knowledge management systems that allow a firm to efficiently retrieve and reuse knowledge and insights from its prior inventions (Ahuja, Lampert, & Novelli, 2012; Garud & Nayyar, 1994; Hansen, Nohria, & Tierney, 1999). Finally, the study also emphasized the importance of external search, even for inside-the-box innovations; making it important for firms to invest in R&D and other related activities which have been shown to enhance absorptive capacity and adding to the consensus that finding a balance between exploitation and exploration is important to create value (Gupta, Smith, & Shalley, 2006).

REFERENCES AVAILABLE FROM THE AUTHORS

Table 1: Negative binomial regressions. Model 1 compares all patents in the sample versus forms of recombination, while Model 2 looks only at recombinations, comparing renewed inventions with recycled ones.

	M1a	M1b	M1c	M2a	M2b
Controls	V***	V***	V***	V***	V***
Recycled inventions			0.025**	-0.088***	-0.150***
			(0.010)	(0.009)	(0.017)
Renewed inventions			0.110***	*default*	*default*
			(0.008)		
Temporal lapse		-0.010***	-0.009***	-0.012***	-0.015***
		(0.001)	(0.001)	(0.002)	(0.002)
Temporal lapse x Recycled					0.011***
					(0.003)
External search		0.003***	0.003***	0.002***	0.002***
		(0.000)	(0.000)	(0.000)	(0.000)
External search x Recycled					0.001**
					(0.000)
Constant	0.741***	0.751***	0.723***	0.895***	0.916***
	(0.037)	(0.037)	(0.038)	(0.055)	(0.055)
Observations	83786	83786	83786	58011	58011
Firms	159	159	159	137	137
Log-likelihood	-265348.53	-265219.08	-265102.21	-182229.502	-182218.754

Standard errors in parentheses. * $p<0.05$, ** $p<0.01$, *** $p<0.001$. *The dummy variable no references is included, but not reported. Year dummies are also included in all models.*