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On the Effectiveness of Patenting Strategies in Innovation Races

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Which, if any, of a firm's inventions should it patent? Should it patent at all? Many companies engaged in an innovation race seek a patenting strategy that balances protection of their intellectual property against the knowledge spillovers resulting from disclosure requirements. Not much is known about factors that determine the patenting strategy best able to resolve this trade-off. Although scholars in various management, economics, and engineering disciplines have researched patents and patenting regimes, little work has addressed the normative issues that pertain to forming an appropriate firm-level patenting strategy. We develop an inventory of real-life patenting strategies and integrate them into a coherent framework. Our simulation model characterizes the optimal patenting choices for different environmental and firm-level contingencies while capturing the dynamics between competing firms. We identify the firm's research and development strategy as the most salient determinant of its optimal patenting strategy. Our research contributes to establishing a contingency theory of patenting strategies.

Keywords: patent strategies; innovation races; NK modeling; games on NK landscapes; strategic interaction on NK landscapes
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1. Introduction

Should a company engaged in an innovation race patent a certain invention? More generally, what inventions should the company patent? (All of them? None at all? A select subset?) And upon what factors should the choice of such a patenting strategy depend?

Consider a case from the semiconductor industry. The Dutch company ASML is practically a monopolist provider of the lithography equipment upon which every advanced semiconductor manufacturer (e.g., Intel and Samsung) relies when developing their next-generation products. Without ASML continuously improving its critical equipment, Moore's law (Moore 1965) would cease to hold. In 2010, ASML faced the challenge of fundamentally revising the architecture of their lithography tools; in particular, the company would need to introduce extreme ultraviolet lithography (EUVL) for its next-generation equipment. So for the first time in a decade, ASML would have to exchange its most critical product component: the light source. Two outside companies—Cymer and Xtreme Technologies—were competing to become the supplier of this light source. Cymer planned to use laser-produced plasma (LPP), whereas Xtreme Technologies planned to use discharge-produced plasma (DPP) (Adee 2010). Although ASML tested both technologies simultaneously (Benschop 2010), in the end only one company would be selected. Xtreme and Cymer were in an innovation race.

This competitive setting resulted in Xtreme Technologies facing a key trade-off when deciding whether or not to patent its inventions. Filing for patents would protect the company's products from being imitated by the competition, but at the cost of disclosure. That is, Xtreme Technologies would have to disclose—well before the affected products could be marketed—the technology it was working on and the kinds of solutions it envisioned. Then Cymer, after analyzing Xtreme Technology's patent application portfolio, could redirect its own research and development (R&D) efforts and possibly "design around" Xtreme's patents before Xtreme's products were even available in the market. In this way, the filing of patents by Xtreme Technologies could unintentionally accelerate a competitive response that might even result in being leapfrogged by its competitor.

The preceding example illustrates the trade-off that all patenting strategies must negotiate. On the one hand, patents protect technological solutions; this prevents competitors from commercializing copied products (traditional patent motive) and may also dissuade competitors from entering a technological area (strategic patent motive). On the other hand, a patenting firm necessarily and clearly discloses its research activities, reveals its location on the technology landscape, and—perhaps most interesting to competitors—gives signals about the quality of solutions resulting from its R&D efforts. Thus, protecting and blocking technologies comes at the cost of sacrificing both secrecy and a possible lead-time advantage.

The case of Xtreme Technologies raises a simple question: Which of its inventions should a firm engaged in an innovation race patent? Answering this question requires knowledge of three related aspects. First, the firm must determine the goal of its patenting activities. Second, it must identify its patenting options. The trade-off just described does not require the firm to choose only between patenting and not patenting for each patent; after all, it is possible to conceive of many different patenting strategies. Third, the firm needs to consider its circumstances. The effects of patenting strategies are not universal and, in particular, their benefits may be contingent on different environmental and firm-level factors. Salient environmental factors include the technology landscape, industry clock speed, and the competitive situation. As for the firm-level factors, it is sometimes difficult to distinguish between R&D strategy and patenting strategy.

Starting with the seminal work of Horstmann et al. (1985), economists have analyzed the behavior of firms that face the trade-off between protection and disclosure inherent in patenting systems (cf. Scotchmer and Green 1990, Waterson 1990, Gallini 1992). These economists employ stylized game-theoretic models to analyze firms' propensities to file for patents. However, their main interest is in solving economy-level problems—that is, giving advice on effective patent regulations—and hence the circumstances that surround the patenting decisions are modeled with a high level of abstraction. The representation of firm-level R&D strategy (as a fully adjustable and rational dynamic research effort) and also that of the firm's patent strategy (as a binary or probabilistic choice for each invention) are convenient for modeling but rudimentary at best. So, despite this rich body of research on patents in innovation races, we lack a comprehensive and nuanced understanding of how firms can design patenting strategies to their competitive advantage while taking environmental and firm characteristics into account.

This paper makes three contributions. First, it constitutes a first effort to devise a *firm-level* theory of patenting in innovation races: we build a coherent inventory of patenting strategies—one that systematizes and complements existing knowledge of such strategies—and then integrate that knowledge into a common framework that incorporates as contingencies the firm's R&D strategy, the technological landscape, and competitor behavior. Second, we provide simulation evidence on the effectiveness of patent strategies as a function of own-firm and competitor R&D strategies, the competitor's patenting strategy, and industry conditions. Our study thus helps lay the foundation for a comprehensive contingency theory of patenting strategies. Third, we introduce the concept of dynamically interacting agents to the NK framework and thereby extend existing methodology. Because the NK framework is well suited to represent the search aspects of R&D, we make it the basis of our modeling efforts. Yet, our research question demands that we explicitly capture the dynamic strategic interactions between firms, so we extend the existing NK methodology accordingly.

2. Motives, Strategies, and Contingencies for Optimal Patenting

Patenting policies are concerned with fostering innovation in the economy (Reinganum 1982, Judd 1985, Gilbert and Shapiro 1990, Klemperer 1990). Such policies need to balance protection requirements, which provide incentives for research, with disclosure requirements, which lead to spillovers and thus accelerate technology development (Scotchmer and Green 1990, Waterson 1990). Hence, when deciding to patent or not, individual firms incorporate the tension between knowledge protection and knowledge leakage (Horstmann et al. 1985, Cohen et al. 2000). The literature has identified several factors that affect how firms handle this trade-off: patent breadth and length (Gallini 1992, Denicolò and Franzoni 2004, Kwon 2012), patent novelty requirements (Scotchmer and Green 1990), the possibility of patenting cumulative and combinative innovations (Erkal 2005, Ottoz and Cugno 2008), the reliability of patent litigation (Choi 1998, Aoki and Hu 1999), imperfect or probabilistic patent protection (Waterson 1990; Anton and Yao 2004; Kultti et al. 2006, 2007), the possibility of patent renewal (Langinier 2004), disclosure requirements pertaining to patents (Bessen 2005, Aoki and Spiegel 2009), and the quality of the focal invention (Horstmann et al. 1985).

As the factors just listed make clear, extant work in the economics literature has (not surprisingly) addressed the effects of a patenting policy on the economy as a whole. In shifting this focus from the economy to the firm we must lower the level of model abstraction in regard to at least three aspects. First, a firm-level patenting theory needs to incorporate more than the outcome measure of overall firm profit. Although the profit motive ultimately drives firm action, the firm may pursue different patenting strategies for a multitude of intermediate goals. A more realistic study of patenting should discuss a patenting strategy's effect on each of those intermediate goals.

Second, a firm-level patenting theory must build a realistic representation of how patenting decisions are made. Traditional economics models represent firm interactions using dynamic games of incomplete information and hence implicitly assume that firms adhere to a very specific and intricate ideal of rationality[1] that no real firm can potentially live up to. In reality, firms are boundedly rational: they adopt behavioral strategies and modify those strategies if they prove not to be useful (Simon 1969). Therefore, a firm-level model should ground its analyses in the main classes of documented behavioral patenting strategies. Moreover, such strategies should allow for repeated decision making about patenting; two-stage games simply do not allow one to represent the complexities that actual decision makers face.

Third, a firm-level patenting theory needs to capture the main contingency factors. In particular, it must adequately represent the firm's R&D process. R&D is fundamentally a search process (Fleming and Sorenson 2001). There is uncertainty ex ante about the outcomes of the search, yet the exploration gives rise to learning in which past searches yield insights that can be used in future searches. It seems likely that the nature of this search process influences patenting strategies.

In this section, we describe the three dimensions that any firm-level contingency model should consider. First, we concentrate on *patenting motives* and thus on the goals to which a firm may aspire. Second, we identify the different *patenting decision* options. Third, we focus on *contingency factors* that determine the usefulness of those decision options—with respect to patenting motives—under different environmental and firm circumstances.

Patenting Motives. Why do firms patent? Empirical studies have carefully examined the motives for patenting—that is, what drives innovating firms to apply for and hold patents (Arundel et al. 1995, Cohen et al. 2000, Macdonald 2004, Sheehan et al. 2004, Blind et al. 2006). These studies provide strong evidence that firms do not patent simply to protect against imitation. Instead they pursue, often simultaneously, a number of strategic goals when applying for a patent (Levin et al. 1987, Cohen et al. 2000, Blind et al. 2006). Although the goals of patenting may appear fairly nuanced in practice, Blind et al. (2006) used factor analysis to condense the multiplicity of considerations into five basic motives: protection, blockade, exchange, reputation, and incentive.

Beyond the traditional *protection* motive, which remains the principal motive for patenting, firms seek to *blockade* competitors by anticipating and preempting their use of future technologies (Ceccagnoli 2009). Such a blockade can serve defensive or offensive purposes: defensive blocking prevents competitors from venturing close to the firm's own technological base (Reitzig 2004); offensive blocking aims to impair competitors' future R&D trajectories regardless of their direction (Granstrand 1999, p. 215; see also Blind et al. 2006). The *exchange* motive presumes that the firm files for patents in order to improve its bargaining position in patent licensing deals (Crama et al. 2008, Aggarwal and Hsu 2009) as well as in patent exchanges and in the cross-licensing of patents (Grindley and Teece 1997). Cohen et al. (2000) and Kash and Kingston (2001) find that the exchange motive is especially important in industries where inventions by competitors build on each other. In the electronics industry, for example, inventions are a composite of many individual detail solutions and so favor cooperation for mutual benefit. Both the *reputation* and *incentive* motives—which are usually considered to be less influential than the motives of protection, blockade, and exchange (Blind et al. 2006)—are linked to the standing a firm has with respect to key stakeholders. The reputation motive involves external stakeholders, such as potential investors (Hsu and Ziedonis 2008); the incentive motive is an internal tool for motivating staff (Oldham and Cummings 1996).

It is important to realize that the three preeminent motives (protection, blocking, and exchange) are intermediate goals. Ultimately, they serve the profit motive by building on a common characteristic of all patents: establishing a claim in the technology landscape that the patent owner can prevent others from exploiting. This claim can be used to protect the firm's position, to prevent another firm from entering a technology field, or to establish bargaining power in an exchange situation. (It is worth remarking that secrecy, the alternative to patenting, can at best achieve only the first of these major patenting motives.) Hence the patent claim can ultimately be

[1] The firm must analyze the competitor's past actions for each individual patent, after which the firm projects *all* of its own and its competitor's actions into the (potentially infinite) future. Based on such projections, the firm makes a globally optimal dynamic decision; it repeats this process for each of its own and each of its competitor's actions.

Table 1 Patenting Strategies on Technology Landscapes

	Patent strategy			
R&D strategy	Everything	High quality	Close competitor	Nothing
Leader	Blanketing/flooding Granstrand (1999), Cohen et al. (2000), Blind et al. (2006, 2009)	Searching for strategic patents Levin et al. (1987), Granstrand (1999), Blind et al. (2006, 2009)	Fencing Lerner (1994), Granstrand (1999), Cohen et al. (2000), Arundel and Patel (2003), Blind et al. (2006, 2009)	Nondisclosing leader Levin et al. (1987), Teece (1986), Cohen et al. (2000), Arundel (2001)
Follower	Surrounding Granstrand (1999), Cohen et al. (2000), Reitzig et al. (2007)	Ad hoc blocking and inventing around Granstrand (1999), Arundel and Patel (2003)	Surrounding (see text) Granstrand (1999), Cohen et al. (2000)	Nondisclosing follower Teece (1986)

used to affect the competitiveness of the firm's product offering and thus to create economic value. For both protection and blocking, that economic value manifests as a *relative* performance advantage of a final product as compared with a competitor's product. Protection gives a focal firm the right to implement its preferred technological solution—a right that it denies the opposing firm. Blockade gives a relative performance advantage to the focal firm by preventing the competitor from implementing its own preferred solution. The exchange motive implies that both companies can break a deadlocked situation and, through collaboration, improve the *absolute* performance of products offered in the market. Our model should therefore account for the roles of protection, blocking, and exchange by examining the performance consequences of staking out claims in a technology landscape.

Patenting Decisions. Motives are not themselves sufficient to establish a patenting strategy. It is only when the firm adopts a consistent decision pattern with respect to patenting that we can speak of its *patenting strategy*. The normative literature on patenting decisions is sparse, with the Granstrand (1999) typology the rare exception. This book reports that firms explore a technology landscape through their R&D processes and then may use patenting to establish and protect claims in this landscape for their exclusive economic use. Based on various case studies across nations and industries, Granstrand (1999, pp. 219–222) identifies six so-called generic patent strategies: ad hoc blocking and inventing around, strategic patent searching, blanketing (or flooding), fencing, surrounding, and combination.

Granstrand's work is a solid starting point for any effort to identify patenting strategies. It is interesting that, upon closer examination, his mapped strategies turn out to be a combination of two *separate* firm decisions. First, the firm's movement (or trajectory) on the technology landscape implies a deliberate decision about the direction of R&D; second, the choice of whether or not to patent a specific technological invention presupposes a patenting rule (or, more broadly, a patenting strategy). Consistently with Granstrand, we recognize that patenting decisions cannot be analyzed without accounting for the firm's overarching R&D strategy (see also Arora and Ceccagnoli 2006, Arora et al. 2008). In contrast with Granstrand (1999), we make a deliberate distinction between the two; thus we are able to systematize and complement current thinking on these strategies.

Table 1 proposes a typological framework for classifying a firm's patenting strategy along those two crucial dimensions, and it classifies the extant literature accordingly. The first dimension is the patenting rule that dictates when an invention should be patented. A firm that patents *everything* seeks patent protection for every solution generated by its R&D activities. A firm that applies the *high-quality* patenting rule files patents only for those solutions that offer superior performance. When patenting under the *close-competitor* rule, a firm tries to anticipate its competitors' future movements and then to patent only those inventions that are in those firms' technology terrains; this rule is most closely related to the blocking motive. The patent *nothing* rule reflects the notion that secrecy will prevent others from exploiting the focal firm's inventions (Levin et al. 1987, Cohen et al. 2000, Arundel 2001); in other words, this strategy seeks to achieve protection by a means other than patenting. The second dimension of our framework is the firm's R&D strategy. Research and development efforts provide the technological solutions eligible for patenting. We follow Teece (1986) and distinguish between *leaders*, who autonomously explore the technology landscape, and *followers*, whose R&D activities are geared to imitate and thus chase competitors' technology trajectories by "inventing around" them.[2]

[2] We assume that followers have enough absorptive capacity to understand the leader's technologies (from patent applications) and can carry out enough R&D themselves to invent around any leader patents: we thus consider *able* followers. This requirement is relaxed in our robustness analyses (see §4.6).

The combination of what we designate a patenting rule and an R&D strategy forms what Granstrand would call a patenting strategy, and our classification subsumes his typology. For instance, the "patent everything" rule followed by an innovation leader that files patents for every solution developed on its path through the technology landscape can be identified as a *blanketing/flooding* strategy; yet, the patent everything decision rule when used by an innovation follower will take the form of a *surrounding* strategy. To avoid confusion, hereafter we shall use the term "patenting strategy" in the more narrow sense of a patenting rule.

Contingency Factors. The two-dimensional classification proposed in Table 1 demonstrates that patenting decisions take effect contingent on a firm's R&D strategy. The same patenting strategy will lead to different outcomes when pursued in combination with a different R&D strategy. Hence we view a firm's R&D strategy as an important *internal contingency factor* for the effectiveness of any patenting strategy. A firm's R&D strategy is long term and difficult to change; its patenting strategy is more malleable. (Of course, R&D strategy is itself a decision variable in the long run; the choice of that strategy is discussed in §5.)

Environmental contingency factors may also moderate how various patenting strategies affect firm goals. Although many environmental factors affect the success of a patenting strategy, two are salient in the literature. First, extensive empirical evidence suggests that a focal firm's patenting behavior should not be analyzed in isolation from the behavior of other firms. This is because observed patenting behavior actually follows from the strategic interactions in so-called patent (portfolio) races (Hall and Ziedonis 2001, Ziedonis 2004, Hall 2005). If a firm suddenly begins to flood entire technological areas with patents, then other firms in the industry adapt by intensifying their own patenting activities (Jell and Henkel 2010). In this case, more patenting simply reduces the risk of being blocked or being sued for infringement (Ziedonis 2004). Thus, competitor behavior is critical to a contingency model of patenting. Since a competitor's patenting likewise takes effect contingent on its R&D strategy, modeling strategic interaction necessarily requires incorporating both the competitor's R&D strategy and its patenting strategy as environmental contingencies for the focal firm. A second factor is industry characteristics—in particular, technological complexity (Cohen et al. 2000) and industry clock speed (Nadkarni and Narayanan 2007). Technological complexity affects how easily innovation can be appropriated in focal markets (Hall and Ziedonis 2001, Ziedonis 2004, Ceccagnoli 2009), and industry clock speed affects how much time each company has to perform its technology search (Chao and Kavadias 2008) and patenting activities (Nadkarni and Narayanan 2007). Any model of patenting should accommodate both of these industry characteristics.

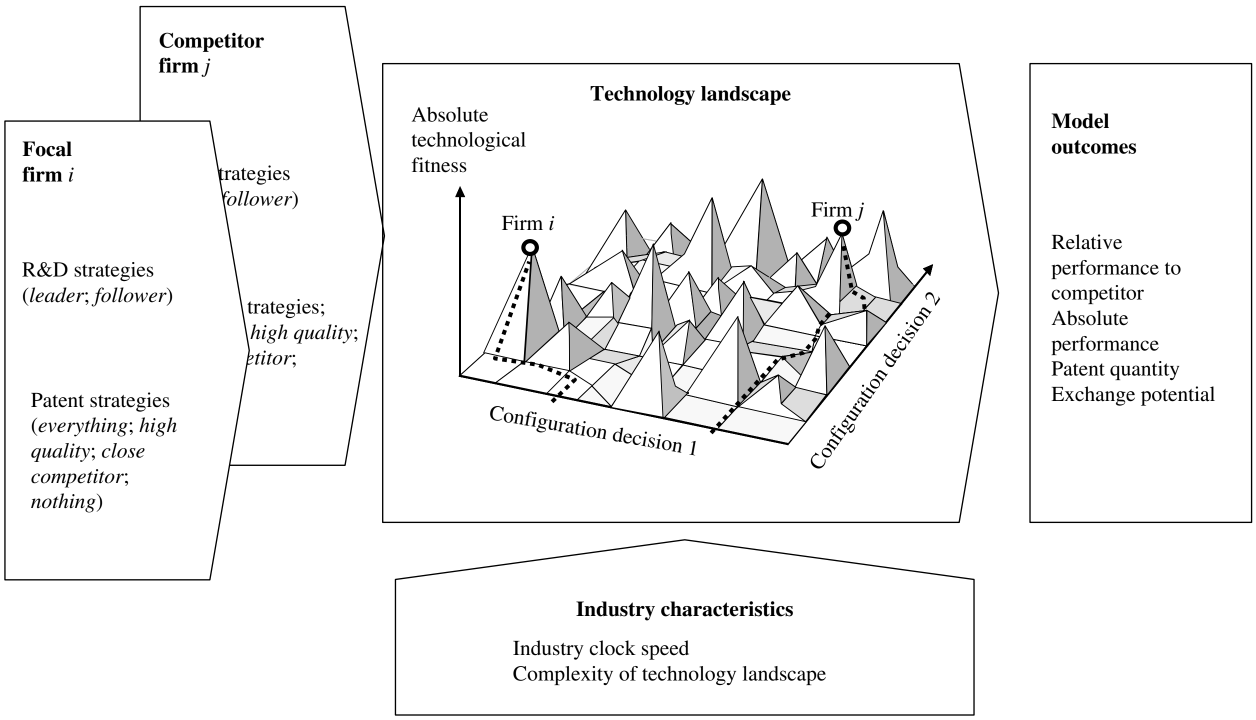
A model fulfilling these requirements would fill an important gap in the literature. It need not accommodate *all* facets of patenting activity (unlike many of the empirical and conceptual works cited in this section), and neither must it focus on the overall economic impact of patent races (unlike models that are primarily economic). Instead, this model aims to create a framework for making decisions about strategic patenting under competition at the firm level. The model abstracts sufficiently from individual details to focus on overall firm patenting strategies, but it is fine grained enough to address questions about how firms should choose their patenting strategies.

3. Model

In §2, we identified critical factors that a contingency model for patenting must consider: *patenting motives* driving competitive advantage and ultimately firm profits as the goal of all patenting activities, *patenting strategies* as the templates for how firms decide on what they ultimately protect, and *internal contingencies* (i.e., the firm's own *R&D strategy*) and *environmental contingencies* (i.e., the competitors' patenting and R&D strategies, industry clock speed and complexity) as mediators between those patenting strategies and the firm's achievement of its patenting goals. Thus the model's predictions must reflect the competitive advantage fostered by patenting motives, the decision variables used in the deployment of patenting strategies, and the parameters needed to reproduce the most salient internal and environmental contingency factors.

A central aspect of our model that helps to formalize these requirements is the notion of a general technology space or "technology landscape" (Granstrand 1999). The technology landscape links agent decisions to outcomes: it models the performance outcome of R&D decisions on a fitness landscape by assigning a fitness value to each of all conceivable technology configurations. The resulting map consists of "coordinates" representing particular product solutions and "altitude curves" assessing the overall technological fitness of those solutions; this map of the landscape thus establishes a basis for the economic value of protection, since a higher technological fitness implies a higher economic value of the resulting products. Hence the fitness dimension represents the competitive situation that patenting motives seek to affect: the economic value embodied in technological fitness can be protected for exclusive exploitation, competitors can be blocked from deriving that value, and it can be used as part of an exchange. Different companies

Figure 1 **Key Elements of the Model**



might search the technology landscape in different ways, thereby implementing different R&D strategies. Contingent on their R&D strategies, firms implement different patenting strategies by reserving (or not) certain locations on the technology landscape for their exclusive use. The various patent strategies can be used to characterize the focal firm's behavior and thus serve as our main decision variables; because they characterize competitor behavior, too, these strategies function also as environmental *contingency factors*. Finally, the landscape's structural properties can be adjusted and so represent additional contingencies pertaining to industry characteristics. Figure 1 provides an overview of our model's elements and their interactions.

Our description of the model begins in §3.1 by explaining how we represent a problem's technology solution as a technology "configuration" and how the technology landscape links technology configurations to fitness outcomes. We continue by assuming the perspective of a focal firm to represent the strategic situation faced by each firm in our model. In §3.2, we explain a firm's implementation of an R&D strategy on a technology landscape; in §3.3, we describe our representation of its patenting strategy. In this way, the firm's patenting decisions are linked to its internal contingency factor (i.e., the firm's R&D strategy). We then show, in §3.4, how an innovation race between two firms plays out, thus connecting the firm's patenting behavior with the most important environmental contingency: the competitor's behavior as shaped by its own R&D and patenting strategy. After thus implementing the main decision variables as well as the main contingency (i.e., competitor behavior), §3.5 is devoted to the other environmental contingencies of interest—namely, industry characteristics. In §3.6, we discuss some noteworthy implications of the model. We shall employ the following notational conventions: $|\mathcal{S}|$ denotes the cardinality of set $\mathcal{S}$ (i.e., the number of its elements); and $\|\mathbf{s}\|$ denotes the Euclidean norm of the vector $\mathbf{s}$ (i.e., its length).

3.1. The Technology Landscape: Linking the Technology Decision to Outcomes

We adopt a standard NK approach (Kauffman 1993, Levinthal 1997) when modeling the technology landscape. Defining a position on this landscape requires that N different configuration decisions s_l be made. These can be viewed as constituting the set of all possible design decisions that go into a technological product. Thus a position—that is, one *technology configuration*—is defined by the decision vector $\mathbf{s} = (s_1, \ldots, s_l, \ldots, s_N)$. For simplicity, the NK model requires that the individual choices s_l be binary (either 0 or 1), so there are 2^N possible technology configurations that an R&D activity can yield. The solution fitness function $V(\mathbf{s})$ maps the N-dimensional technology configuration $\mathbf{s}$ into a one-dimensional performance measure, thereby generating an altitude profile over the N-dimensional technology landscape. The performance so measured captures the resulting product's competitiveness in the market place.

One benefit of using the NK model is that we can then structurally alter the technology landscape's complexity as follows. Each decision contributes to the overall fitness. Let V_l denote the contribution of decision l to fitness. Then the overall fitness is simply the average of all the decisions' contributions:

$$V(\mathbf{s}) = \frac{\sum_{l=1}^{N} V_l(s_l, \mathbf{s}_{-l})}{N}.$$

Landscape complexity arises because V_l depends not only on the value of s_l but also on the value of K other decisions (Levinthal 1997, Levinthal and Warglien 1999); we denote these decisions as $\mathbf{s}_{-l} = (s_{l1}, \ldots, s_{lK})$. For each possible combination of s_l and $\mathbf{s}_{-l}$, a random draw from a uniform distribution $U[0, 1]$ is assigned to $V_l(s_l, \mathbf{s}_{-l})$. When $K = N - 1$, decisions are highly interdependent: each V_l is affected by all $N - 1$ other decisions and so the technology landscape is uncorrelated, complex, and "rugged." If one of the N decisions changes, then all V_l assume the value of another random draw, which means that the entire fitness function V takes on the value of a new random draw. As a result, nearly identical technological solutions may result in drastically different technological performances (Baumann and Siggelkow 2013, Ethiraj and Posen 2013). At the other extreme, if $K = 0$ then all decisions are independent because V_l depends exclusively on s_l; hence the technology landscape is correlated, not complex, and "smooth." In this case, if one of the N decisions changes then only the corresponding V_l undergoes a random change, which means that V is only marginally affected. Consequently, a slight product modification will have a comparably slight effect on performance.

3.2. R&D Strategies

The technology landscape links each technology configuration to an outcome. We can therefore model the R&D search process as a search on the technology landscape (Mihm et al. 2003, Sting et al. 2011). In the standard NK model, a firm searches the landscape in isolation and its search heuristics are motivated by various behavioral factors (Levinthal 1997, Knudsen and Levinthal 2007). Deviating from standard instances of the NK approach, we model *two* firms that explore the technology landscape while interacting with each other. For each firm $i, j = 1, 2$, $i \neq j$, the search process starts from a random initial product solution $\mathbf{s}_i^{(0)}$ and then traverses the landscape via the search trajectory $(\mathbf{s}_i^{(t)})_{t \in \mathbb{N}} = (\mathbf{s}_i^{(0)}, \mathbf{s}_i^{(1)}, \mathbf{s}_i^{(2)}, \ldots)$.

To illustrate the model dynamics and firm interactions, we consider an arbitrary period t in which both firms have already undertaken some R&D activities. Each firm has investigated the technological field to a certain extent and has thus built a knowledge base of that field; furthermore, each firm has protected some of this knowledge by using patents. In our model, a firm that has built knowledge of a field corresponds to a firm that has explored some technology configurations $\mathbf{s}_i^{(\tau)}$ and learned about their performance $V(\mathbf{s}_i^{(\tau)})$ for all past periods $\tau \in \{1, \ldots, t\}$. The complete stock of knowledge that the firm has assembled prior to the current period t is retained in the solution list $\mathcal{S}_i^{(t)}$, which stores all technology configurations that the company has explored and their respective performance; a second list, the patent list $\mathcal{P}_i^{(t)}$, contains all solutions for which the firm has filed a patent by t and their respective performance. Clearly, $\mathcal{P}_i^{(t)} \subseteq \mathcal{S}_i^{(t)}$. Although $\mathcal{S}_i^{(t)}$ is private information to firm i—since we assume that, in general, firms do not reveal their R&D activities to their competitors—the competing firm j can observe the subset of patented (and thus disclosed) solutions $\mathcal{P}_i^{(t)}$.

In §2 we established the R&D leader and the R&D follower as exponents of two archetypical R&D strategies. These two strategies are represented by different heuristics in our model. Consider the beginning of the period $t + 1$, when the firm needs to decide about its future R&D direction. It must choose an area of research—that is, a starting point for its R&D efforts. A *leader* firm chooses its starting technology configuration from its solution list $\mathcal{S}_i^{(t)}$, relying exclusively on its own technology. In contrast, a *follower* focuses on catching up with the leader; hence a follower chooses its starting technology configuration from its competitor's patent list $\mathcal{P}_j^{(t)}$. Neither the leader nor the follower necessarily choose the best-performing technology available to them as their starting point. Instead they pick a starting configuration randomly, with the selection probabilities proportional to the assessed quality of each solution. Building on the base technology chosen, the firm carries out an incremental research step. That is, the firm experiments with one randomly chosen decision by reversing its state from 0 to 1 (or vice versa). This R&D step generates the next solution $\mathbf{s}_i^{(t+1)}$ and its performance $V(\mathbf{s}_i^{(t+1)})$, updating the solution list from $\mathcal{S}_i^{(t)}$ to $\mathcal{S}_i^{(t+1)}$.[3]

3.3. Patenting Strategies

Once firm i has carried out its R&D efforts with result $\mathbf{s}_i^{(t+1)}$, it must decide whether or not to patent this technological solution. As described in §2, firms may apply different patenting strategies.

Under the patent everything rule, the firm files a patent for any solution that is not covered by a previous patent filed by either the firm or its competitor; formally, it files a patent when $\mathbf{s}_i^{(t+1)} \notin \{\mathcal{P}_i^{(t)} \cup \mathcal{P}_j^{(t)}\}$.

[3] We assume that the follower has full absorptive capacity (Cohen and Levinthal 1990, Lenox and King 2004)—in other words, that it can readily assess the leader's patents and easily integrate them into its own R&D program. This simplifying assumption (which we relax in §4.6) renders the model more parsimonious.

Table 2 Patent Strategies: Base Terrains for New R&D Activities and Patent Criteria for Firm i at Time $t+1$

	Patent strategy			
R&D strategy	Everything	High quality	Close competitor	Nothing
Leader	R&D base: $\mathcal{S}_i^{(t)}$ Patent new solution $\mathbf{s}_i^{(t+1)}$ if $\mathbf{s}_i^{(t+1)} \notin \{\mathcal{P}_i^{(t)} \cup \mathcal{P}_j^{(t)}\}$	R&D base: $\mathcal{S}_i^{(t)}$ Patent new solution $\mathbf{s}_i^{(t+1)}$ if not patented and $V(\mathbf{s}_i^{(t+1)}) > \max\{V(\mathbf{s}) \mid \mathbf{s} \in \mathcal{P}_i^{(t)}\}$	R&D base: $\mathcal{S}_i^{(t)}$ Patent new solution $\mathbf{s}_i^{(t+1)}$ if not patented and $\min\{\|\mathbf{s}_i^{t+1} - \mathbf{s}\| \mid \mathbf{s} \in \mathcal{P}_j^{(t)}\} = 1$	R&D base: $\mathcal{S}_i^{(t)}$ Patent nothing
Follower	R&D base: $\mathcal{P}_j^{(t)}$ Patent new solution $\mathbf{s}_i^{(t+1)}$ if $\mathbf{s}_i^{(t+1)} \notin \{\mathcal{P}_i^{(t)} \cup \mathcal{P}_j^{(t)}\}$	R&D base: $\mathcal{P}_j^{(t)}$ Patent new solution $\mathbf{s}_i^{(t+1)}$ if not patented and $V(\mathbf{s}_i^{(t+1)}) > \max\{V(\mathbf{s}) \mid \mathbf{s} \in \mathcal{P}_i^{(t)}\}$	R&D base: $\mathcal{P}_j^{(t)}$ Patent new solution $\mathbf{s}_i^{(t+1)}$ if not patented and $\min\{\|\mathbf{s}_i^{t+1} - \mathbf{s}\| \mid \mathbf{s} \in \mathcal{P}_j^{(t)}\} = 1$	R&D base: $\mathcal{P}_j^{(t)}$ Patent nothing

Under the "patent high-quality" rule, the firm files a patent only if the solution is unpatented and of higher quality than any previously filed patents by the firm—formally, only if $V(\mathbf{s}_i^{(t+1)}) > \max\{V(\mathbf{s}) \mid \mathbf{s} \in \mathcal{P}_i^{(t)}\}$. Under the "close-competitor" patent rule, the firm files a patent only if the solution is unpatented and could easily be copied by the firm's competitor. A solution is considered to be "easily copyable" if it is adjacent to one of the competitor's patents, by which we mean that the latter can be derived from the former via a single mutation. Formally, the focal firm's patent is *adjacent* to a competitor's patent if $\min\{\|\mathbf{s}_i^{(t+1)} - \mathbf{s}\| \mid \mathbf{s} \in \mathcal{P}_j^{(t)}\} = 1$. Finally, under the "patent nothing" rule, the firm applies for no patents. If the firm chooses an active patenting strategy (one of the first three just described) and if the firm decides to apply for a patent, then the solution $\mathbf{s}_i^{(t+1)}$ will be added to $\mathcal{P}_i^{(t)}$ and will yield the updated patent list $\mathcal{P}_i^{(t+1)}$. Table 2 summarizes all the combinations of R&D types and patenting rules.

In addition to deciding whether or not to patent a specific invention, the firm must account for how much space its patent can claim in the technology landscape. In many industries, companies tend to file for basic patents—especially in industries with "compound" or "complex" products (Cohen et al. 2000). Basic patents protect not only a single solution but also the technological core of that solution in adjacent applications. For instance, nearly all semiconductor manufacturers had to honor the patent held by Texas Instruments for the CMOS transistor (Weber 1990). However, other companies can file their own patents as refinements of the basic patents. Virtually all semiconductor manufacturers patented some detail aspects of the CMOS transistor (or its production). The result was an "interlocking" scenario whereby manufacturers were able to block each other from choosing an optimal transistor design. Even Texas Instruments could not manufacture its own semiconductors without using the inventions protected by competitors' patents. In practice, an interlocking scenario is an economic incentive for patent exchange.

In the context of our model, basic patents protect not just one point but instead an entire area in the technology landscape. Let parameter $B \geq 0$ denote a patent's *breadth*, where $B < N$. The technological core of a patent is defined by $N - B$ technology decisions, which are fixed. Thus, basic patents protect the neighborhood around a specific solution by covering B undefined decisions. Whereas a specific patent grants the firm the right to exploit a particular solution, a basic patent establishes the firm's stake in a wider technology space. For example, let $N = 5$ and $B = 2$, and let the specific solution be the configuration $\mathbf{s}_i^{(t+1)} = (11101)$. Suppose the technological base of this specific patent consists of the first three decisions; so by filing a basic patent, the firm protects the technological neighborhood of $(111 \cdot \cdot) = \{(11100), (11101), (11110), (11111)\}$. Provided that $B > 0$, the corresponding neighborhood of $\mathbf{s}_i^{(t+1)}$ will also be included in the updated patent list $\mathcal{P}_i^{(t+1)}$ as basic patents. Note, however, that both competing firms will associate the patented neighborhood solutions with $V(\mathbf{s}_i^{(t+1)})$—that is, with the evaluation for the specific solution. In line with observations indicating that firms aim to establish patent stakes as broadly as possible, we assume that the company prefers to file basic patents with $B = 2$ (if existing patents do not preclude the firm's doing so); we choose the $N - B$ basic decisions randomly. If the firm is prevented from filing a basic patent by conflicting extant patents, then the firm narrows the breadth of the focal patent: first to $B = 1$ and then, if necessary, to $B = 0$. A basic patent protects the firm's stake in ramified technologies, but it does not grant the firm an exclusive right to exploit them. In other words, the competing firm may file a specific patent even if there is already a basic patent that protects the underlying area (provided, of course, that there is no specific patent already). This scenario corresponds to the case of specific patents establishing details of a solution as they build on the core technology of a broader basic patent. In our model, as in the real-life example, either firm can then prevent the other from using the invention because the basic patent and the specific patent interlock; this standoff sets the stage for a patent exchange.

3.4. Model Dynamics and Model Outcomes

Having delineated the model's individual elements, we can now describe overall dynamics and ultimate payoffs. Each firm starts from a random point in the landscape and then, iteratively, (a) carries out research by mutating one decision in the N-dimensional decision vector and assessing its performance; (b) decides, based on its patenting strategy, whether or not to patent and then, if necessary, updates its patent list; and (c) identifies, based on its R&D strategy, the starting point for carrying out research in the next round.

Each firm searches the landscape by repeatedly going through this cycle until the time ends in period T. The model parameter T can be viewed as the market clock speed, which is an exogenously given deadline for presenting the product solution. A small T implies substantial time pressure for R&D efforts, whereas a large T corresponds to business situations with long market cycles that allow for in-depth R&D exploration (Csaszar and Siggelkow 2010, Mihm et al. 2010).

By the end of period T, firm i receives the payoff associated with its *highest-quality solution* $\mathbf{s}_i^*$ that is not already patented by the competitor. In other words, the firm launches the product with the highest performance that is not protected by the competition. Hence it does not matter whether firm i holds a patent for $\mathbf{s}_i^*$; what matters is whether firm j has already patent-protected the technology solution $\mathbf{s}_i^*$. Formally, firm i achieves the *absolute performance*

$$\Pi_i = \max\{V(\mathbf{s}) \mid \mathbf{s} \in \mathcal{S}_i^{(T+1)} \backslash \mathcal{P}_j^{(T+1)}\}, \quad i = 1, 2, \ j \neq i.$$

However, the firm's market success may depend less on this absolute performance than on its relative performance—that is, as compared with the competitor's solution. Some strategy profiles yield good absolute performance but poor relative performance. We view relative performance as being well proxied by (relative) market share; we view absolute performance, which indicates a solution's overall attractiveness, as being well proxied by market size. In the rest of this paper we report both the absolute performance and the relative performance achieved by each firm i, where *relative performance* is formally defined as

$$\Pi_i^r = \Pi_i - \Pi_j, \quad i = 1, 2, \ j \neq i.$$

Previously, we described how, for a given product solution, one firm's specific patent may overlap with a basic patent held by another (competing) firm. In such cases, a product cannot be brought to market without the competitor's consent. The result is a deadlock in which *neither* party can exploit the patented product solution. To examine such situations, we augment our simulation results by incorporating the potential value of patent exchange. This value is defined as a firm's expected performance increment that would result from breaking the patent deadlock via mutually shared patents. In our simulations, no agent chooses to participate in a patent exchange; we simply indicate the value of patent exchange once game outcomes have been realized.

Finally, we consider patenting *cost* to be linear in the number of patents filed. For c the average direct and indirect cost per patent, the accumulated patenting cost could be given as $C_i = c|\mathcal{P}_i^{(T+1)}|$ ($i = 1, 2, \ j \neq i$). However, we intentionally refrain from including an explicit cost factor. For some companies, small improvements in competitiveness (relative performance) outweigh any patenting cost considerations; yet for other companies, even considerable performance advantages are quickly outweighed by the cost of acquiring and maintaining patents. We therefore report the raw *number* of patents $|\mathcal{P}_i^{(T+1)}|$.

3.5. Industry Characteristics

We have elaborated on the main internal and environmental contingencies by embedding both the focal firm's R&D strategy as well as the competitor's R&D and patenting strategies into the model's dynamic structure. Two critical parameters allow us to address the contingencies involving industry characteristics. First, we can capture industry clock speed by systematically varying the time T allotted to a simulation run. Second, by changing the correlation parameter K in the NK representation of the technology landscape, we can account for search environments that are relatively more or less complex.

3.6. Implications of the Model

It is worth making explicit one aspect of the model that has so far been implicit. What is the relation between our four performance metrics above—absolute and relative performance, exchange potential and cost—and (what most models assume is) the ulterior goal of firm action: financial payoff? Why do we refrain from modeling payoff directly?

From a conceptual perspective, our model (i) accounts for the possibility that the firm's patenting strategy affects its technology position (and, indirectly, the technology position of its competitor) and (ii) views the firm's technology position (and that of its competitor's) as key drivers of financial results. Obviously, financial payoffs are also affected by other factors—including firm factors, such as its commercialization capability (Arora and Ceccagnoli 2006), and environmental factors such as demand uncertainty. Some of these other factors (e.g., commercialization capabilities) moderate the technology position's effect on financial payoffs. One approach to representing this notion formally would be to devise a function that maps all important technology position parameters and all the "other" factors to a financial payoff. However, such a mapping would require devising a specific function for how these factors influence payoffs, and we would thus be bound to introduce potentially limiting assumptions. The less constraining approach chosen in this paper is to refrain from defining a function explicitly; rather, we enumerate the most important aspects of a technology position that determine profit—as identified in the empirical literature on patenting motives—and analyze how patenting strategies influence those aspects. This way, readers can draw their own conclusions about financial payoffs. The approach developed here is both parsimonious and yet generalizable.

A second aspect of the model is worth noting. The model's time horizon is T, where T corresponds to the launch of the product that commercializes a particular technology. Hence, and in line with existing literature on patents (e.g., Horstmann et al. 1985), our model focuses on the innovation race. It is possible that, upon product launch, the product itself causes knowledge spillovers to competitors. When these are large, relative differences in performance at the end of the innovation race are worth less in financial terms. When spillovers are small, relative differences in performance yield a higher payoff.

4. Analysis

In this section we discuss the effectiveness of patent strategies. The analysis is organized in terms of our main contingency: competitive behavior determined by the combinations of opposing R&D types. Thus we report (in §§4.1–4.4, respectively) the results for (1) how a leader should shape its patenting strategy when competing with another leader, (2) how a leader should compete against a follower, (3) how a follower should compete against a leader, and (4) how a follower should compete against another follower.

We set the end time T to 100 rounds; we set $N = 12$ and $K = 6$ so that the reported performance measures reflect a moderately complex environment. (The effects of varying these parameters are discussed in §4.6.) Given that simulation-based results are subject to random fluctuations, we report averages of 10,000 runs for each game setting. In each run, the players compete on a new random landscape constructed using identical parameters. All results mentioned in the text are significant at the 5% level.

4.1. Best Strategies for an R&D Leader Competing with an R&D Leader

First we consider the case of a leader competing against a leader. Figure 2 plots all the outcome measures described previously. The figure's upper left quadrant shows the relative product performance (i.e., how well the focal firm fares when compared with its competitor) at the end of the innovation race: the more positive the relative performance, the more competitive the focal firm's product; the more negative, the less competitive. The upper right quadrant shows the number of patents held by the focal firm at the end of the innovation race—recall that this number is used as a proxy for patenting cost. The figure's lower left quadrant shows the focal firm's absolute product performance, which is a proxy for the product offering's attractiveness to consumers and thus for market size. The lower right quadrant illustrates the product performance gains that the firm could achieve via patent exchange. The higher the potential gains from patent exchange (for both firms), the greater the likelihood that such an exchange will take place.

In each quadrant, the horizontal axis depicts the focal firm's possible strategies and the vertical axis marks out the various performance indicators associated with the (same four) possible competitors' strategies. We identify these competitor strategies by using dots of different color. Thus the 16 dots in each quadrant fully characterize each combination of strategies played by the focal firm and its competitor.

We start by concentrating on the relative performance of the final product. We assume that the firm begins its analysis of patenting options by establishing whether or not it is capable of beating the competition.

The firm tailors its strategy so that it can react optimally to competitor actions; in other words, the firm strategy is designed to be optimal given that the competitor chooses a certain strategy. The firm develops such an optimal plan for each possible competitor strategy. Then, while assuming that its competitor also behaves strategically, the firm tries to second-guess its competitor's actions. We juxtapose the competitor's optimal plan for every given competitive situation in turn. In other words, the firm devises best responses for every contingency (i.e., for each competitor patenting strategy) that maximize its own position—relative to the competitor's. A competitor that behaves likewise will determine its own strategy while assuming that the focal firm is also employing a best-response strategy. Neither player has an incentive to deviate from the equilibrium that arises from this dynamic. In fact, we can formally define a simultaneous move game over the behavioral strategies identified in previous sections; the action set consists of the four archetypical strategies identified by the empirical literature. This approach allows us to identify the Nash equilibria of the game. We remark that the firms need not be aware of the game in order

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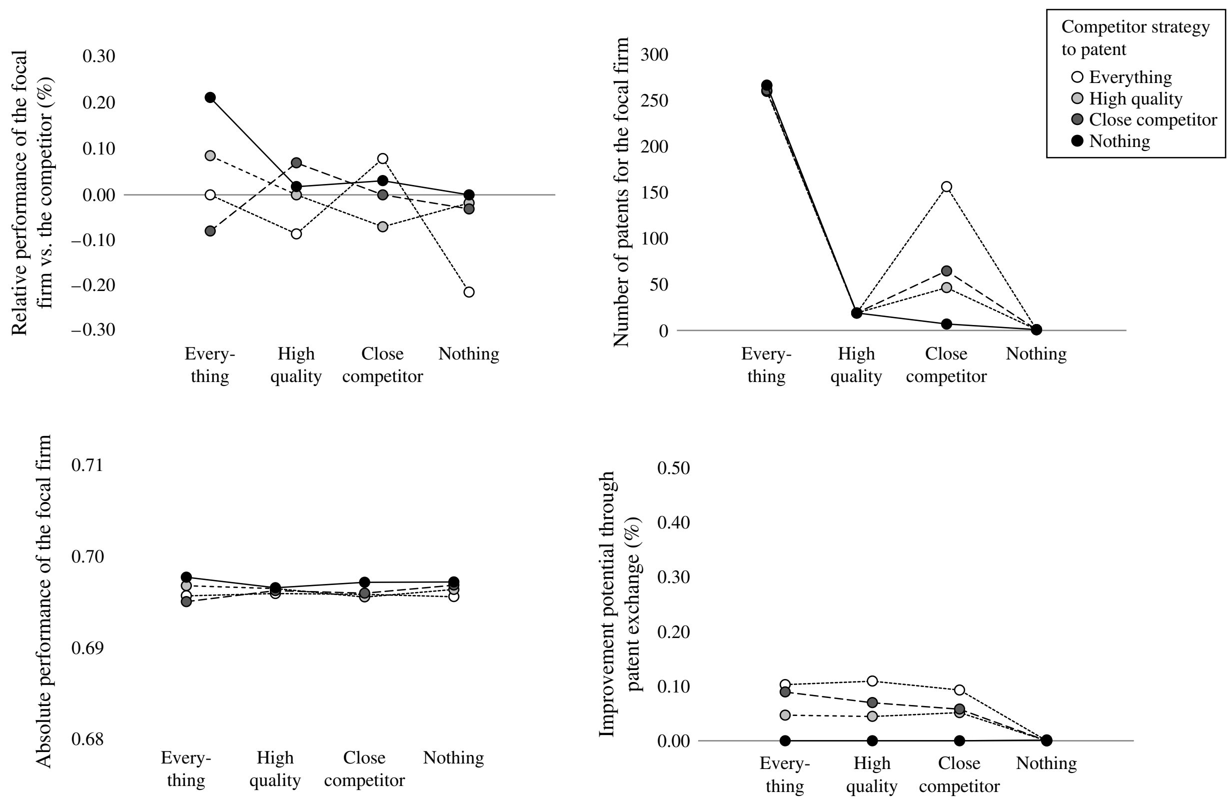
Figure 2 **Results for a Leader Competing with a Leader**



for it to play out as described. If each competitor continues to adjust its patenting strategy in reaction to the other competitor's move—continually trying to find a better strategy—then this evolutionary process may reach the same state of equilibrium (see, e.g., Nelson and Winter 1982).[4]

Our analysis begins with a discussion of best responses before focusing on the outcomes of various equilibria. Observe that all the figures represent each competitor patenting strategy using identically shaded dots that are linked by a uniquely depicted (dots, dashes, etc.) line. The firm identifies its best response to a competitor's strategy by choosing as its own strategy (on each plot's x-axis) the one with the highest y-axis value on that line. For instance, if the competitor patents nothing (line of black dots) then the focal firm's best response is to patent everything—in other words, to choose the highest (here, the leftmost) black dot.

Figure 2 supports several notable conclusions. In response to a competitor that patents nothing (line of black dots), pursuing that same strategy (rightmost black dot) yields poorer performance for the focal firm than does any of the other, active patenting strategies (leftmost three black dots). Moreover, given any competitor strategy (any line of dots), the relative performance of patenting nothing (right-column dots) is either inferior to or not significantly different from any of the other three patenting strategies (corresponding dots in the other columns with identical shading). For example, a strategy of high-quality patenting clearly dominates the strategy of filing no patents. In short, to patent nothing is an inferior strategy for a leader competing with a leader. The effect is not large but it is relevant.

Among the three active patenting strategies, no single one dominates. Although patent everything is the firm's best response when its competitor patents nothing, high-quality patenting should be employed in response to close-competitor patenting and close-competitor patenting is the best response to a competitor that patents everything. So from the relative performance viewpoint, a leader facing a leader should definitely patent; however, none of the active patenting strategies is clearly preferable.

In fact, for leader-leader competition, neither absolute product performance nor the potential gains from a patent exchange is enough to determine the best active patenting strategy. The lower left quadrant of Figure 2 clearly shows that, with respect to absolute performance, no active patenting strategy dominates any other. The same is true when we analyze patent exchange (lower right quadrant): no active patenting

[4] See §5 for an in-depth discussion of our equilibrium concept.

strategy dominates and, overall, the potential gains from a patent exchange would be small. So as regards relative and absolute performance and also patent exchange, all active patenting strategies are consistent with the goal of achieving good product performance for leaders that are competing against leaders.

Yet with regard to the number of patents held by the focal firm at the end of the technology race, the strategies exhibit substantially different results (upper right quadrant). In particular, the strategy of patenting everything naturally results in many more patents than do the other two active strategies. So if the cost of filing for—and holding—patents is substantial, then the strategies of high-quality and close-competitor patenting outperform the patent everything strategy, which rational players should therefore avoid. However, if the cost for patenting is negligible and if a high number of patents held yields secondary benefits, then it is actually preferable to patent everything.

In sum, for an R&D leader engaged in a race with another technology leader, active patenting is the optimal strategy. The classical protection motive of patenting outweighs any secrecy considerations. Since our competitive setup is symmetric, such a patenting strategy also forms the industry equilibrium. (In equilibrium, the firms' best responses reciprocally agree; no firm benefits by unilaterally deviating from active patenting.) We therefore expect that, in markets of competing technology leaders, considerable patenting activity will be observed. Since the differences between the various active patenting strategies tend to be small, we expect to find a spectrum of different active strategies in practice.

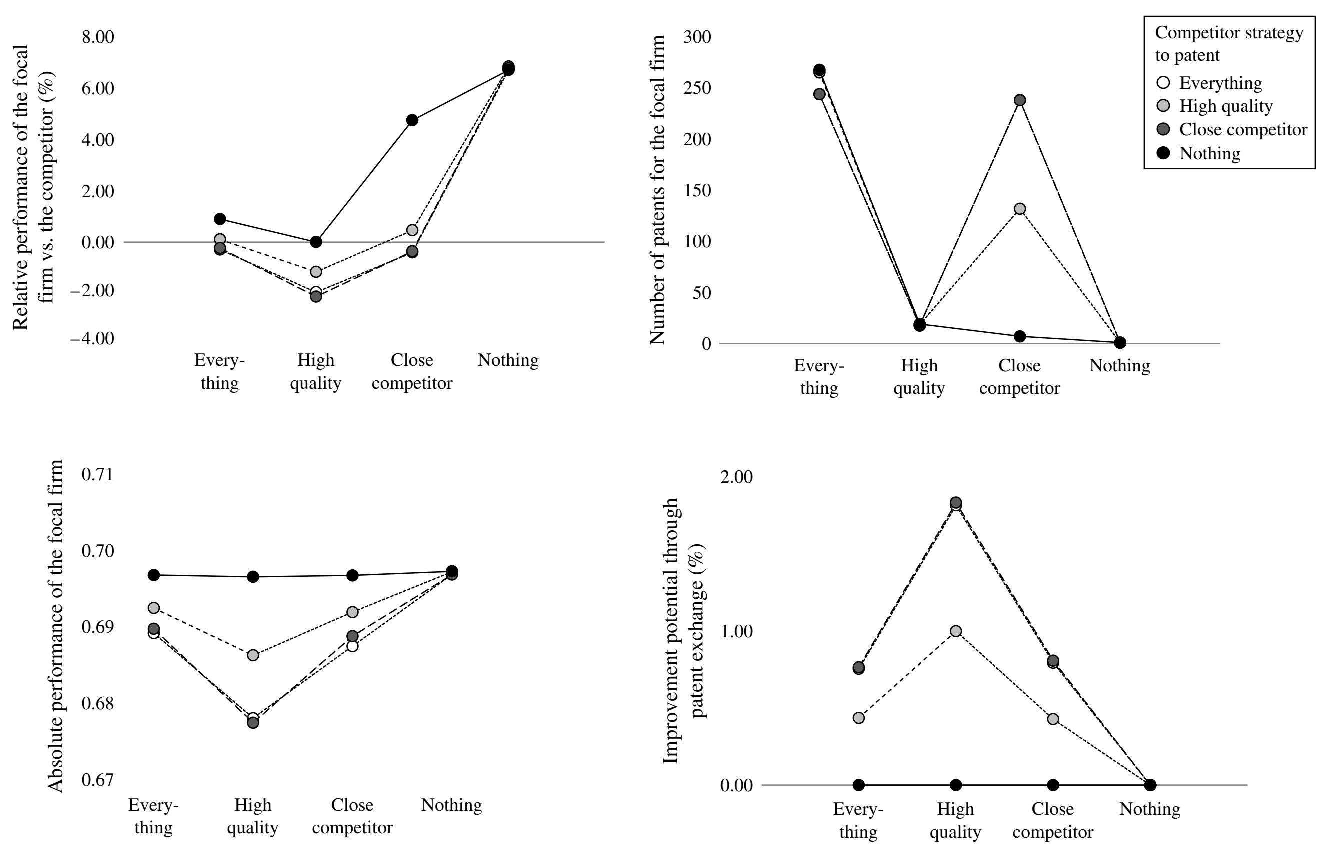
Because both competitors adopt a symmetric active patenting strategy, neither can use patenting to differentiate itself in the market; their product performance is roughly equivalent. Hence both companies are better off exchanging their patents: doing so increases the absolute product performance of each firm without affecting the competitive stalemate. We therefore expect patent exchange schemes to be prevalent.

4.2. Best Strategies for an R&D Leader Competing with an R&D Follower

We now turn our attention to an asymmetric setting in which a focal R&D leader competes with a follower. How should the leader protect its inventions against a follower? How should the leader respond to a follower's anticipated patenting strategies?

For this leader-follower combination, Figure 3 shows the relative performance, the number of patents held

Figure 3 **Results for a Leader Competing with a Follower**



at the end of the race, the absolute performance, and the expected gains from a patent exchange for the focal R&D leader. If we focus on relative performance in order to identify best responses, then it is clear that patent nothing is the leader's dominant strategy irrespective of the follower's strategy; to patent nothing is to outperform any active strategy, and by a considerable margin. Therefore, the leader should not reveal information about its R&D trajectory by patenting, even though not patenting means that the leader cannot formally protect its technology position should the follower happen upon it. The performance advantage of a leader competing against a follower stems from secrecy: the follower has no reliable information concerning where its research efforts should be focused. In contrast, any strategy that includes patenting will provide a signal that the follower might use to improve its performance substantially.

Unlike the case of leader-leader competition, in this case there are subtle but interesting differences that allow for distinctions among the active patenting strategies. Among these, the strategy of patenting only high-quality innovations is an especially inferior choice. This insight contradicts the common intuition that companies should build patent portfolios consisting solely of high-quality patents in order to balance protection and the cost of patenting. To the contrary, we find that a leader firm adopting the strategy of high-quality patents is more easily outperformed (than are leader firms adopting other active patent strategies) by its follower: the better the signal for the follower (i.e., the more clearly the leader identifies filed patents as superior ones), the easier it will be for the follower to find desirable and perhaps even superior solutions in the technological vicinity of the leader's inventions. The follower wastes no time on inferior solutions, focusing instead on the most promising technology configurations as devised (and signaled) by the leader. The implication is that, if a leader must patent, at least it should avoid signaling the solution quality when competing against a follower. When the leader either patents everything or patents close to its competitor, much of the patenting does not involve superior technological solutions and thus confounds more than facilitates the follower's R&D efforts.

With the number of patents serving as a proxy for patent cost, the expenditures required under the different strategies reinforce the superiority of the patent nothing strategy, which is cost optimal by definition. It is noteworthy that, among the active patenting strategies, the close-competitor patenting strategy may yield the same number of patents as does the patent everything strategy.

Neither analyzing absolute performance nor analyzing the gains from patent exchange meaningfully distinguishes the benefits and drawbacks of the different patenting strategies. The strategy of patenting nothing is no less beneficial for absolute performance than is any active patenting strategy. And even though the potential gains from a patent exchange are naturally higher for the active patenting strategies, such gains can at best compensate for the absolute performance disadvantages of the corresponding active strategy in comparison with having patented nothing in the first place. Thus the patent nothing strategy is unequivocally optimal for an R&D leader competing with a follower.

We have established how a leader should respond to any of the follower's patenting strategies. Next, toward the end of characterizing industry equilibria, we analyze which strategy a follower should choose.

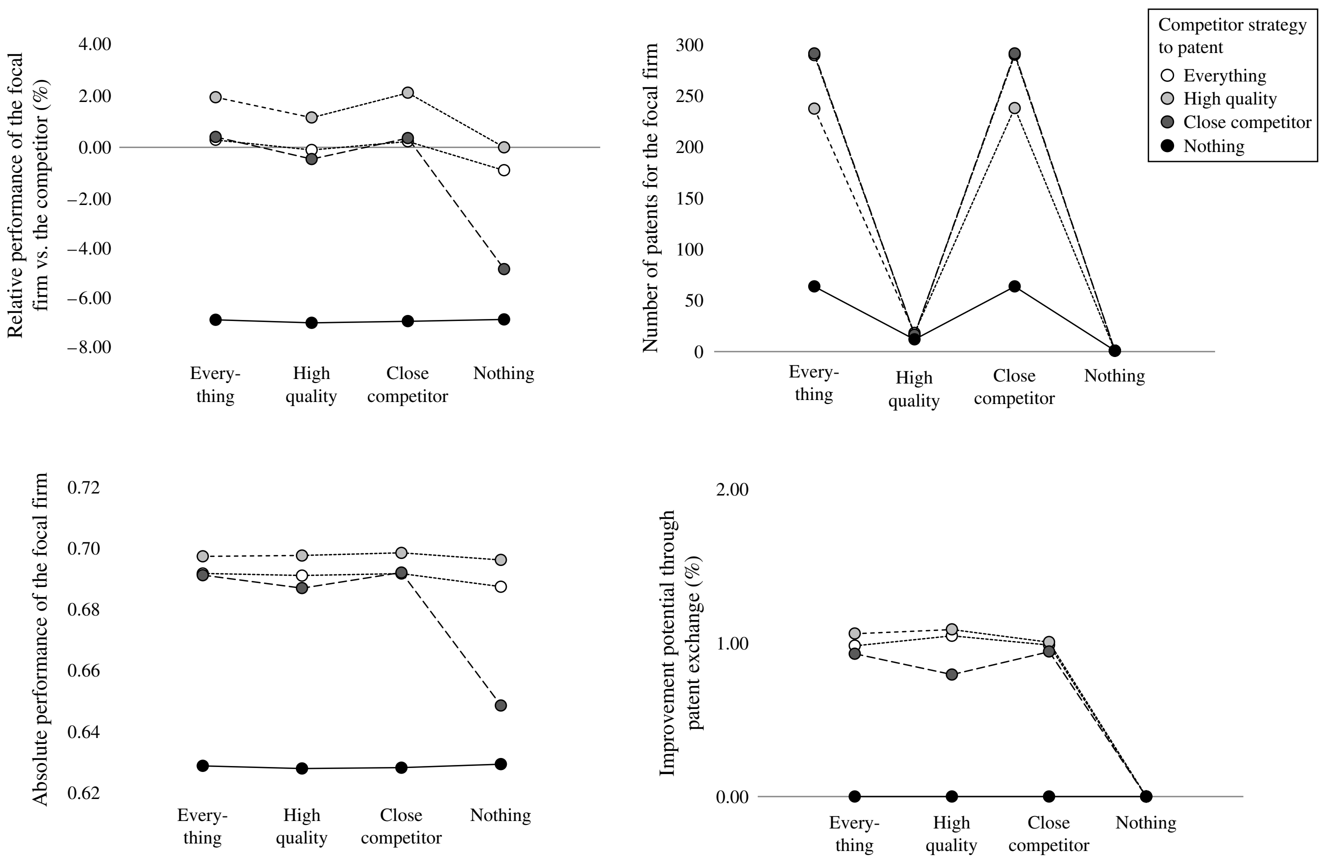
4.3. Best Strategies for an R&D Follower Competing with an R&D Leader

In this setting, our focal company is an R&D follower and its competitor is an R&D leader. Thus we reverse the previous setting's perspective by now assuming the role of the follower.

As usual, Figure 4 displays all four dimensions of performance for the focal firm. With regard to relative performance, the follower clearly benefits from an active patenting strategy regardless of the strategy chosen by its competitor: any active strategy is no worse (and usually better) than not patenting at all. The intuition behind this result is that, by choosing an active patenting strategy, the follower claims technology positions in the vicinity of the leader's technology positions and thus secures positions that the leader itself might otherwise have claimed via patenting or picked as a product solution at some later stage; in this case, the follower carries out "offensive blocking (and inventing around)." The effect of this blocking is amplified if the follower receives high-quality information about favorable technology regions from the leader's strategy to patent only high-quality innovations, in which case the follower might actually outperform the leader. But even when the leader hides its R&D advances by not providing any patent signals, active patenting by the follower entails at least some possibility that it will block a potentially superior invention by the leader.

Which strategy (among the active choices) should the follower prefer? Patenting everything and close-competitor patenting exhibit the same relative performance and cost. This similarity is expected because the follower (by definition) expends its research efforts in the technological vicinity of the leader and so, simply by virtue of implementing a close-competitor strategy, patents everything. However,

Figure 4 Results for a Follower Competing with a Leader



a patent everything strategy decidedly outperforms solutions based on high-quality patenting—albeit at a substantially higher cost. Hence a trade-off results: if cost is a critical consideration, then the follower should patent only high-quality innovations; if patenting costs are negligible, then the follower should patent everything.

These recommendations remain valid even after we take into account both absolute performance and the potential gains from patent exchange. As compared with the strategy of no patenting, none of the active strategies exhibits inferior product performance. Moreover, after accounting for the potential benefits of a patent exchange, the absolute performance of the different strategies becomes virtually indistinguishable.

Now that we have analyzed the best responses for both leader and follower, the expected equilibrium follows easily. The leader patents nothing because this strategy is optimal regardless of the competing follower's choice of strategy. In contrast, the follower either patents everything or selectively patents high-quality products. Note that the leader's *not* patenting precludes any patent exchange with the follower.

4.4. Best Strategies for an R&D Follower Competing with an R&D Follower

We now consider the final setting, in which one follower competes with another. Overall, as shown in Figure 5, the best responses in terms of relative performance resemble those of a follower competing with a leader.[5] Irrespective of the competitor's strategy, the strategies of patenting everything and of close-competitor patenting (weakly) dominate the strategy of patenting nothing and clearly dominate the strategy of patenting only high-quality innovations. Accounting for absolute performance reinforces the dominance of these two strategies: the high-quality patenting strategy remains slightly inferior both to patenting everything and to close-competitor patenting. Considering the potential value from patent exchange at best equalizes absolute performance among the three active strategies, but it leaves the patent nothing strategy as an inferior option. Finally,

[5] A paradoxical outcome results from one follower patenting actively while another follower patents nothing. Suppose the second follower patents nothing and instead builds upon patents of the first. But since the first follower does not have a firm to follow, it would linger on the initial (randomly chosen) position while the second follower profited from the first's inventions. We therefore disregard cases in which only one of the followers patents.

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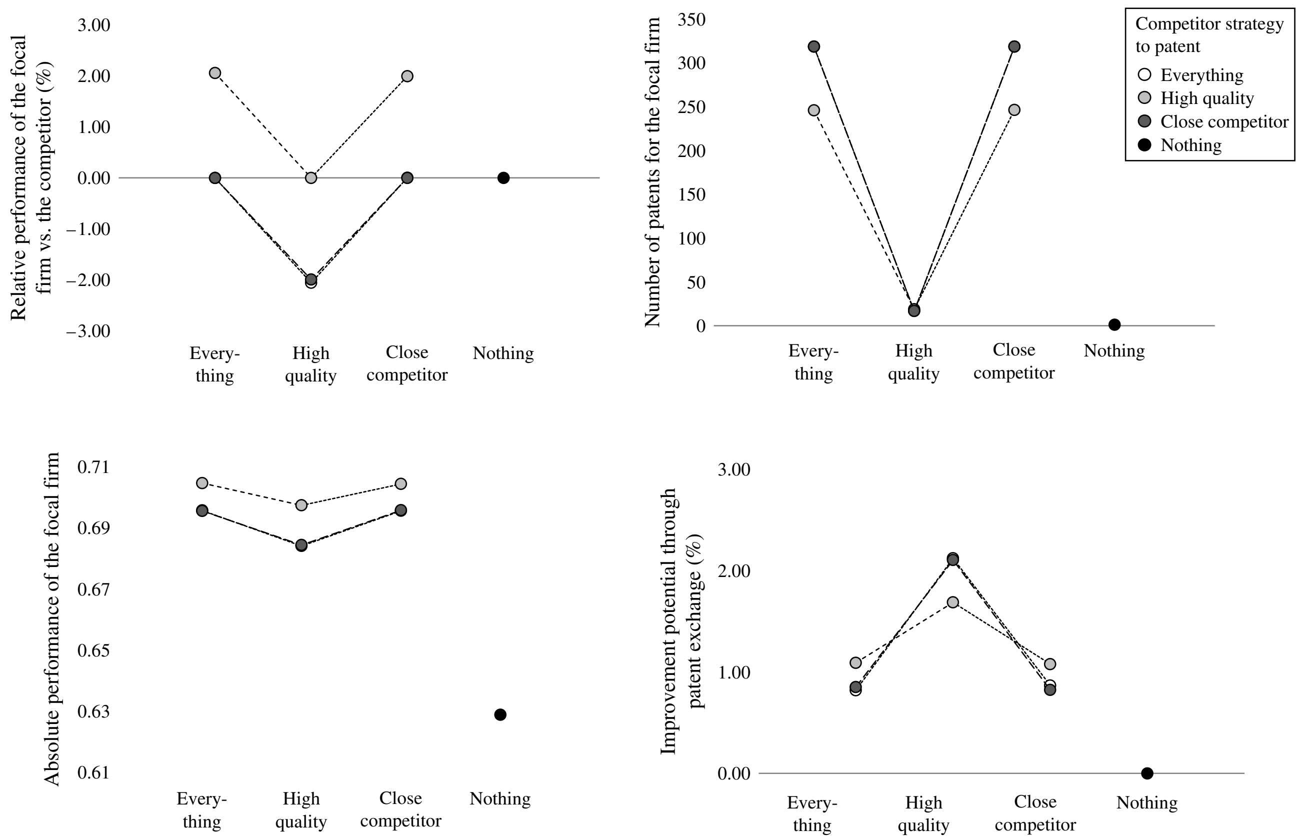
Figure 5 Results for a Follower Competing with a Follower



as expected, patenting nothing is less costly than any active patenting strategy. Among the active strategies, high-quality patenting is the cheapest because its overall cost is close to that of patenting nothing. Therefore, if performance is the firm's dominant concern, then it should pursue an active patenting strategy—preferably patent everything or close-competitor patenting. Yet if cost outweighs other considerations, the high-quality patenting strategy is evidently the best option.

In equilibrium, we should therefore expect both players to pursue either a strategy of patenting everything or a strategy of patenting only high-quality inventions, depending on whether (respectively) performance or cost considerations dominate. Since the patenting strategies chosen by the competitor are symmetric, we expect that the two parties will engage in a patent exchange to increase absolute performance. It is noteworthy that two followers exploring a technological landscape can produce an absolute level of performance comparable to that reached in races involving a leader. The reason is that two actively patenting followers function, in effect, as a research cartel. Instead of one company searching the landscape, the two follower companies combine their research efforts and dynamically propel each other's performance.

4.5. The Value of Patent Analysis

In the preceding discussion, each leader pursued its own R&D agenda and ignored any information about the innovation activities of its competitor; this setup reflected a working assumption that a leader does not expect technological advances to arise from its competitors. Now, however, we shall examine the value of patent analysis from the leader's perspective. How valuable is the ability to analyze competitors' patents and then absorb the embodied innovations into the firm's own research program? How do the patent strategies and R&D types of the players affect the value of patent analysis? Will the capacity to analyze patents affect outcomes of the competition?

For the purpose of this analysis we introduce the *analyzing leader*. The analyzing leader bases the choice of where next to focus its R&D efforts not only on the portfolio of its own past explorations but also on the patented solutions of its competitor. Formally, we have the following: An analyzing leader i that seeks to investigate a new technological configuration chooses a starting point for its R&D effort from $\mathcal{S}_i^{(t)} \cup \mathcal{P}_j^{(t)}$; in contrast, a conventional leader j (which does not perform patent analysis) bases its choice of starting point solely on solutions resulting from its own R&D activities, $\mathcal{S}_j^{(t)}$. All other elements of the model (in particular, the functioning of patent and R&D strategies) remain unchanged.

However, we introduce a contingency in this context of an analyzing leader. Previously, we followed the dominant search paradigm (Fleming and Sorenson 2001) and implemented a localized incremental R&D search in which firms identify new locations for R&D efforts via a random change in one decision. Yet research is sometimes characterized by a radical departure from existing practice as when the company explores completely new avenues (cf. Smith and Tushman 2005, Ceccagnoli 2009). To represent such radical (distant) search behavior, we create one model variant that allows for "long jumps." Technically, we follow Levinthal (1997) in supposing that, whenever the firm carries out research, it evaluates both a local move (changing one decision at a time) as well as a long jump (changing N decisions simultaneously) to arrive at a random new position, selecting the move that offers higher performance. All results presented in the preceding sections still hold under this generalization (see §4.6) and hence merit no further discussion. In the context of patent analysis, however, conceptualizing R&D as combined local and distant search does affect the results and hence requires explicit exposition.

Because we now take the perspective of a leader deciding whether or not to implement patent analysis, we reconsider the outcomes of the "leader versus leader" and "leader versus follower" settings discussed previously. We focus on relative performance as our key metric in order to establish likely behavior and equilibrium outcomes. (Taking into account absolute performance and the value of patent exchange does not alter any of our conclusions.) As a second metric, we establish the value of patent analysis per se; this value is assessed in terms of the gains expected by an analyzing versus a conventional leader. Thus we make two comparisons: (i) the case of an analyzing leader competing with a conventional leader to the case of a conventional leader competing with a conventional leader; and (ii) the case of an analyzing leader competing with a follower to the case of a conventional leader competing with a follower.

For our first analysis, we focus on companies engaging in incremental search. The upper left panel of Figure 6 plots the relative performance for an analyzing leader competing against a conventional leader. This figure indicates that, as a best response to any active patenting strategy, active patenting strategies (preferably, patenting everything or close-competitor patenting) dominate patenting nothing and also that, as a response to patenting nothing, active patenting strategies at least weakly dominate patenting nothing. Hence an analyzing leader should choose an active patenting strategy and refrain from patenting nothing.

Choosing an active patenting strategy was the equilibrium outcome for both conventional leaders in the base setting of §4.1. Although it might therefore seem as if an analyzing leader's best response is in line with such an equilibrium outcome, patent analysis modifies the equilibrium fundamentally. To see this, note that gains for the analyzing leader are losses for its competitor, the conventional leader. The conventional leader cannot choose a strategy such that it wins, whereas the analyzing leader can realize positive gains for each choice by the conventional leader—that is, for each line in the graph. However, the conventional leader can limit the analyzing leader's gains by choosing not to patent. Thus the analyzing leader's choice of an active strategy forces the conventional leader to adopt the strategy of patenting nothing. The conventional leader thereby reduces the risk of being constrained by a "patent girdle" devised by the analyzing leader. Hence the equilibrium shifts from two conventional leaders patenting actively to one analyzing leader patenting actively and one conventional leader patenting nothing.

This analysis of relative payoffs is reinforced by the upper right panel of Figure 6. The graph in this panel compares the equilibrium of two competing conventional leaders with the equilibrium of an analyzing leader competing with a conventional leader. In the symmetric equilibrium of two conventional leaders patenting everything (leftmost point of the connecting lines), both firms perform at the same level. If one of the conventional leaders begins to analyze the other's actions (and so becomes an analyzing leader), then the equilibrium shifts. As a result, the analyzing leader can now harness the conventional leader's R&D efforts and so enjoys a relative benefit from introducing patent analysis. Overall performance for the analyzing leader climbs to a slightly elevated level.

An important takeaway is that the analyzing leader is better off for having engaged in patent analysis, which creates a relative benefit and even a small absolute benefit for the company.

Examination of an analyzing leader and a conventional leader engaging in *radical search* yields substantially different insights. With respect to best-response functions, the lower left panel of Figure 6 is strongly similar to the upper left one. Again, the analyzing leader's best response to any competitor strategy is to choose an active patenting strategy. However, this equilibrium is fundamentally different than the one for firms engaging in incremental search. An active strategy does not guarantee that the analyzing leader will dominate the competition. Rather, if the conventional leader chooses to patent everything then the

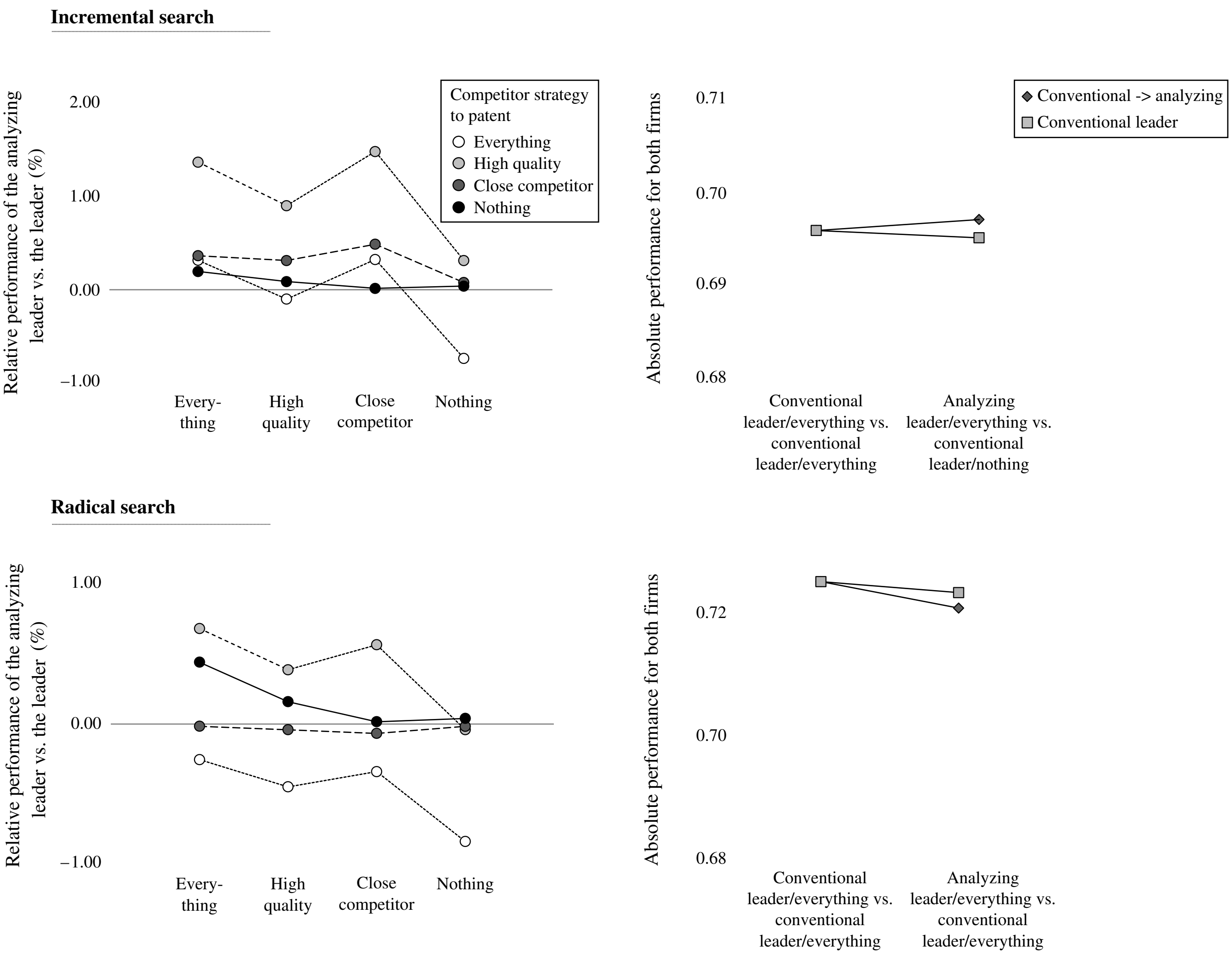


Figure 6 Results for an Analyzing Leader Competing with a Conventional Leader

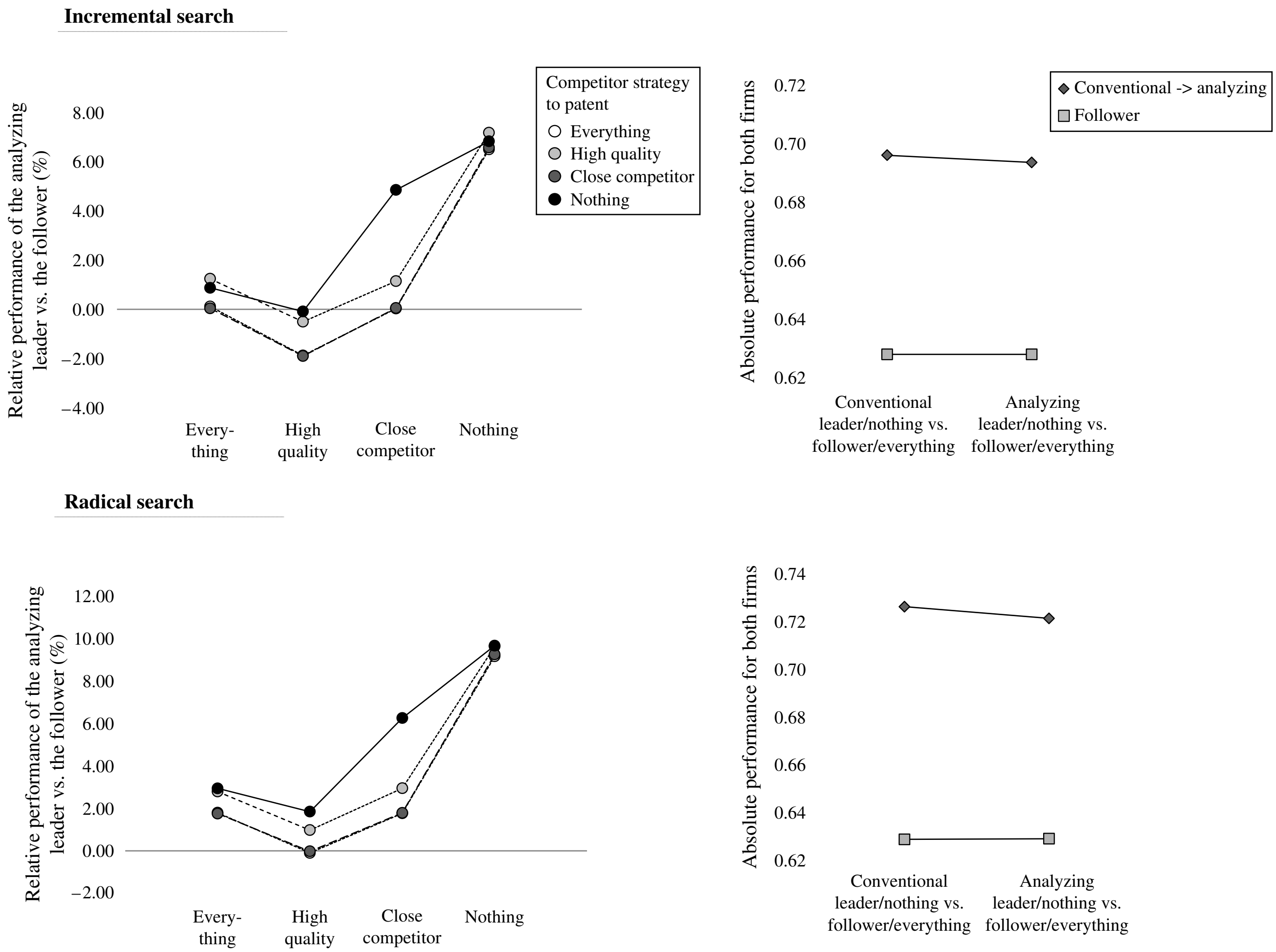
analyzing leader can at best attain a slightly negative relative performance, which means that the conventional leader outperforms the analyzing leader. In equilibrium, of course, the conventional leader will choose to do so. Hence the equilibrium will be a conventional leader patenting everything and the analyzing leader choosing one of the active strategies.

Why does the conventional leader win the competition? Both players are capable of performing radical innovations—that is, both can search broadly. The analyzing leader may further broaden its search by adopting competitor positions as new bases for its own R&D efforts. However, when following and inventing around another player, the analyzing leader risks wasting valuable R&D efforts by searching in the (perhaps densely protected) neighborhood of the competing conventional leader. So for a leader who can already search broadly, it is better *not* to rely on another leader's patents; the equilibrium outcome negates the value of patent analysis in the case of radical search. Patent analysis could actually be harmful for the company engaging in it, which explains why no rational firm would perform patent analysis in environments characterized by radical search.

The upper (respectively, lower) left panel of Figure 7 plots for the incremental (respectively, radical) search case the relative performance of an analyzing leader competing against a follower. The analyzing leader's patent analysis capabilities do not qualitatively alter the best responses of a conventional leader as described in §4.2. Regardless of the follower's strategy, the analyzing leader should patent nothing; and, as before, the analyzing leader should definitely avoid patenting only high-quality solutions. The follower responds by choosing to patent everything. Hence, in the case of an analyzing leader competing with a follower, patent analysis does *not* alter the prevailing equilibrium.

However, two comparisons reveal a remarkable consequence of that equilibrium. The equilibrium point in the upper left panel of Figure 7 is lower than the corresponding point in Figure 3. The upper right

Figure 7 **Results for an Analyzing Leader Competing with a Follower**



panel of Figure 7 shows a decline: in equilibrium—under which the leader chooses to patent nothing and the follower chooses to patent everything—the analyzing leader is actually worse off than a conventional leader in terms of both absolute and relative performance. The decline is not large but it is relevant: the follower does not have enough information to launch promising R&D initiatives itself. In fact, the follower's R&D efforts are largely undirected. Hence the follower produces substantial quantities of low-quality patents. Such patents perturb the analyzing leader's patent analysis and so diffuse the leader's own R&D initiatives. Moreover, the analyzing leader's strategy to patent nothing does not protect against the infringements that are likely to occur when novel R&D initiatives are inspired by the follower's patents. This problem is inherent to patent analysis unless the analyzing leader is able to distinguish *perfectly* between better and worse solutions. It would be unrealistic to assume such capacities in a firm so patent analysis is definitively not recommended for leaders that compete with followers.

The results of this section are worth highlighting. In contrast to our intuition, patent analysis need not improve the performance of the analyzing leader—even if it has the capacity to assimilate competitor innovations into its R&D program (Cohen and Levinthal 1990). In fact, patent analysis may prove harmful: an analyzing leader that competes with a conventional leader benefits only when both carry out incremental search; the analyzing leader encounters deteriorating performance when both engage in radical search. In the case of an analyzing leader competing with a follower, patent analysis simply does not add value for the analyzing leader.

The pattern of when analysis is beneficial versus harmful is quite intricate. Our results may therefore explain why competitive patent analysis is neither widely promoted in the literature nor used in practice as a standard tool for establishing R&D strategies (Fabry et al. 2006).

4.6. Industry and Additional Firm Characteristics

We have implicitly assumed throughout our analyses that the most critical moderating influence on the optimal choice of a patenting strategy is the market's competitive dynamics—that is, whether the focal firm is an R&D leader or follower and whether this firm is in competition with a leader or a follower. However, other variables at the industry level and the firm level may also affect the choice of patenting strategy.

Industry-Level Influences. At the industry level, we have systematically varied two of the most central factors: the technology landscape's complexity and the innovation race's search time. Landscape complexity is a proxy for how many acceptable solutions exist to a given technological challenge and for how difficult it is to find them. A complex landscape may have several solutions, but they will be difficult to identify. Many different technologies might offer a similar performance, and competitors can then "avoid" each other. A simple landscape has relatively few solutions, which are easily identified by surveying the current configuration's neighborhood. As a result, only a limited set of technologies achieves a reasonable level of performance and so different companies' research efforts will quickly coalesce around those technologies. Search time is our proxy for different industry clock speeds. Some markets require that products be extremely mature; a new technology must undergo several iterations before a solution merits marketable production (Sommer and Loch 2004). In other, more experimental markets, technologies may be quickly translated into marketable products without much iteration. This explains why innovation races quickly terminate in some markets but span extensive periods of time in others.

Both of these factors could well affect the optimal strategy in a given situation. We therefore systematically vary both complexity (using $K = 0$ and $K = 11$ rather than the main model's $K = 6$) and the length of the race (10 and 200 steps rather than the main model's 100 steps). It is remarkable that variations in complexity and/or in timing do not change our results. Although the reported effects become more pronounced for higher complexities and less pronounced for shorter times, our qualitative conclusions remain valid in any case. These analyses imply that firms, when choosing their patent strategy, should not focus on industry clock speed or the technology landscape's specific shape. Instead, the most critical determinants of an optimal patenting strategy are the characteristics of the innovation race's competitors.

Alternative Firm-Level Factors. Finally, we describe the effects that two additional firm-level characteristics could have on how patent races unfold. The first characteristic is the search behavior of the leader. Firms may engage in both incremental and radical R&D activities. To accommodate the possibility of radical innovation, we extend our model to include long jumps (cf. Levinthal 1997). The results for a leader competing with a leader or a follower do not change; however, as laid out in §4.5, the value of patent analysis is definitively affected by the introduction of long jumps.

As for the second characteristic, the follower may not be able to (fully) discern the quality of the patents filed by a leader; in other words, it may lack absorptive capacity. So that our model can accommodate such lack of capacity, we have the follower pick at random the (leader) patent on which to base its R&D efforts, instead of picking it based on its inherent quality. This modification of the model does not affect the conclusions that we draw from the analysis, as our results remain robust with respect to a follower with less absorptive capacity. It seems that given enough time, the follower will run across the leader's more promising patents eventually.

The lack of absorptive capacity could alternatively be conceived as all firms (whether leader or follower) being unable to understand the value of the technology configuration that they have discovered. Such an error could arise from the randomness associated with any commercialization issue, or could more simply be explained by insufficiently capable firms. We accommodate this alternative conceptualization in the model by having the firms base their decisions not on the technology configuration's actual value but rather on a the landscape value plus a white-noise term (normally distributed with $\mathcal{N}(0, 0.05)$). Once again, the results are affected quantitatively but not qualitatively: all our conclusions continue to hold.

The last two results underscore an important fact. The leader cannot use the follower's lack of ability to protect itself; instead, the leader must actually pursue the strategy of not patenting anything.

5. Discussion

Theoretical research on patenting has examined the trade-off between patent protection and disclosure of information at the level of specific innovations (e.g., Horstmann et al. 1985). These models conceptualize the decision of patenting versus secrecy either as a binary choice or as continuous substitutes that are traded off by a "propensity to patent." Using this convenient abstraction, the model-based literature has established the "nature of the innovation" and the "industry with its ruling patent regime" as factors that determine optimal resolutions of the trade-off between patenting and secrecy. In line with those predictions, empirical research on patenting has provided broad evidence that firm-level patenting activities are heterogeneous *across* industries (Hall et al. 2014). Yet, empirical research has also suggested that patenting strategies vary even *within* industries (e.g., Cohen et al. 2000). In addition, there is evidence

Table 3 Summary Framework of Main Results

	Competitor firm	
Focal firm	Leader	Follower
Leader	Active patenting Patenting high quality Patenting close competitor Both perform equally well Patent exchange	No patenting Leader wins No patent exchange
Follower	Active patenting *If cost is a consideration*: Patent high quality *If cost is not a consideration*: Patent everything (or close competitor) Leader wins No patent exchange	Active patenting *If cost is a consideration*: Patent high quality *If cost is not a consideration*: Patent everything (or close competitor) Both perform equally well Patent exchange

that patenting activities of firms operating in industries with stable characteristics and unchanged patent regimes can nonetheless change over time (Jell and Henkel 2010). Our model contributes to reconciling this apparent inconsistency between theoretical predictions and empirical findings by adopting a more fine-grained and dynamic perspective on patenting: in our coevolutionary framework, the effectiveness of a patenting strategy emerges as being intricately connected to the firm's own R&D strategy and linked also to its competitors' R&D and patenting strategies.

In this paper we identify contingencies that affect the choice of a patenting strategy and then characterize the optimal choices with respect to those contingencies. As do previous models, we incorporate structural industry characteristics as contingency factors. Yet even though technological complexity and industry clock speed influence patenting *outcomes*, they have no appreciable effect on the choice of an optimal patenting *strategy*. In contrast, the firm's strategy is substantially affected by competitive dynamics that stem from its own and its competitor's research strategy and from its competitor's patenting strategy. Hence the optimal strategy is a function of (1) whether the firm is competing against an R&D leader or a follower, (2) whether the firm itself aims to be a leader or a follower, and (3) what patenting choices the competitor usually makes. Our model thus explains heterogeneity in patenting strategies by hitherto omitted contingencies such as variations in the R&D strategies of incumbent firms. We pay particular attention to the realism of our modeled patenting strategies by grounding them in the well-documented behavior of actual firms. Table 3 summarizes our main results.

In sum, we find that if an R&D leader competes with another R&D leader then both should pursue an active patenting strategy. A strategy of patenting only high-quality innovations is preferable for both parties, with the strategy of close-competitor patenting a near second. When an R&D leader is competing with a follower, the leader should patent nothing and the follower should either patent everything (if patenting costs are negligible) or patent only high-quality inventions (if patenting costs are high). Finally, if two followers compete with each other then both should employ either a high-quality patenting strategy (if patenting costs are high) or a patent everything strategy (if those costs are negligible).

Patent exchange is likely to occur when a leader competes against a leader or when a follower competes against a follower, since in both of those cases the exchange is mutually beneficial. However, patent exchange is unlikely when a leader competes with a follower because only the leader would benefit from the exchange.

This paper also sheds light on the value of patent analysis for R&D leaders. Patent analysis makes competitive information available to the analyzing leader and thus could be assumed to give it an edge. In contrast to that intuition, however, patent analysis need not actually improve the performance of an R&D leader: its value depends intricately on the nature of the R&D activity. If the firms are engaged in incremental search of the technology landscape, then patent analysis is beneficial for the leader because it creates a relative benefit and also a small absolute benefit. But if the firms are engaged in radical search, then a different conclusion emerges: patent analysis does not yield benefits and may, in fact, be harmful to the extent that the leader is thereby induced to chase potentially harmful competitor ideas. Patent analysis is ambivalent. The overall usefulness of patent analysis is thus limited, which hints at the fundamental reason why—despite its prima usefulness—such analysis has not become a standard tool in R&D strategizing.

We have explicitly assumed that the R&D strategy is determined by factors external to the model; hence the company's only decisions concern its patenting strategy. In the long run, though, the research strategy in itself may be a decision variable. Our patenting analysis can yield some insight on such a combined R&D and patenting strategy as follows.

The equilibria of the different settings exhibit different levels of stability with respect to changes in the R&D strategy. Can any of the players improve their performance by changing their R&D strategy? If so, then evolutionary forces will eventually drive them to realize that improvement potential. When a follower competes against a follower, both perform at about the same level and patent their results. Yet by adopting the behavior of an R&D leader, a follower could become relatively more competitive and thus win the technology competition—unless the follower can reap substantial cost savings in R&D. Hence the scenario in which two followers are competing against each other is not a stable one in technology-dominated industries. Now consider what happens when a leader competes against a follower. The follower patents, but the leader refrains from patenting and is able to win the innovation race. Hence this scenario, too, is unstable (again barring R&D cost advantages). The remaining follower should therefore attempt to become an R&D leader. In contrast, the equilibrium in which a leader competes against another leader is a stable one. Both firms perform at about the same level, and both patent using similar strategies. Most importantly, switching to a follower role would entail losses in relative performance. Overall, then, the follower role is transitional; it does not exhibit long-run stability in industries that are dominated by technological performance.

From a methodological point of view, one of our choices deserves critical reflection. We conceptualized the choice of patenting strategies as a simultaneous-move game over a set of predefined strategies. Alternatively, we could have formulated a dynamic game in which players proceed in rounds: (i) analyzing new competitor patents and potentially imputing information about competitor moves that were not patented (e.g., the search location and the quality of the outcome), (ii) deciding on their own search location; and (iii) based on that outcome, deciding whether or not to patent. Solving such a game would automatically yield the optimal patenting behavior as well as the optimal R&D search behavior. However, such an equilibrium would require that, *at any time* the firm not only build an entire map of the documented search locations of its competitor (the competitor's patents) but also make inferences about its competitor's unpublished search locations using a precise probability distribution over the number of search locations, their precise coordinates, and their potential outcomes. The equilibrium would also require that the firm project its own and its competitors' actions—including the potential search outcomes into the (possibly infinite) future—and then, based on such projections, make a globally optimal dynamic decision on whether or not to patent. Although we do not dispute the value of an academic effort to characterize such equilibria, we believe that the implicit information processing requirements cannot be met by any real-life company. Similar considerations led Simon (1969) to devise the concept of "bounded rationality." In our context, bounded rationality would lead firms to adopt behavioral strategies and to refine those strategies if they prove unsuccessful. Such behavioral strategies do not need to be static, and may well allow the firm to adjust its behavior dynamically in response to competitor moves. However, such adjustments are formulated as contingencies ex ante: the policy contains "what if" statements. The realism of such behavioral strategies comes at a cost, however. The action set contains only predefined strategies, so no new strategies can emerge. Hence it is important for the quality of our analysis that we identify the appropriate archetypes among the behavioral strategies. Fortunately, we could ground our work in an extensive empirical literature (e.g., Granstrand 1999) that has identified these archetypes. Yet we acknowledge that, in order to limit complexity, the strategies addressed here span only the most salient classes of patenting strategies. There may be strategy variants that would yield improvements over the cases we have treated.

A second aspect of our paper requires consideration when interpreting the results. The analysis is based on a formal model that is investigated via computational means; absent an accompanying empirical analysis that verifies the conclusions, our patent strategy advice should be viewed with an appropriate level of skepticism. That being said, the recommendations derived from our model form immediately testable hypothesis about the most likely patenting strategies in different competitive situations.

In conclusion, this paper has developed a set of normative prescriptions for how companies should make use of patents in innovation races. In so doing, our research has taken a meaningful step toward a contingency theory of patent strategies.

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