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THE PERSISTENCE OF KNOWLEDGE-BASED ADVANTAGE: AN EMPIRICAL TEST FOR PRODUCT PERFORMANCE AND TECHNOLOGICAL KNOWLEDGE

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Resource-based theory maintains that intrinsic characteristics of resources and capabilities, such as their tacitness, complexity, and specificity, prevent imitation and thereby prolong exceptional performance. There is little direct evidence to verify these claims, yet a substantial literature encourages firms to formulate competitive strategies around resources with these attributes. Further, work outside the resource-based tradition suggests that these attributes can slow innovation, and it is not clear when this effect outweighs the benefits of inimitability. This paper seeks to clarify whether and how the complexity, tacitness, and specificity of a firm's knowledge affect the persistence of its performance advantages. We find that the complexity and tacitness of technological knowledge are useful for defending a firm's major product improvements from imitation, but not for protecting its minor improvements. The design specificity of technological knowledge delayed imitation of minor improvements in this study. Copyright © 2002 John Wiley & Sons, Ltd.

Knowledge-based competition is an area of intense interest to strategic management scholars and practitioners alike. In fact, many claim that knowledge is the most important source of competitive advantage and sustained superior performance (Drucker, 1995; Spender and Grant, 1996). Researchers investigating this topic have typically anchored their work in the resource-based theory of the firm, which suggests that complex, specialized, tacit knowledge generates more durable advantages because it is difficult to imitate (Winter, 1987; Reed and DeFilippi, 1990). However, few studies have empirically linked knowledge to exceptional performance, or investigated how knowledge-based advantage is sustained (Teece, 1998a).

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This lack of empirical evidence is troubling given the normative emphasis on knowledge with these characteristics as a source of advantage (Lei, Hitt, and Bettis, 1996; Grant, 1996; Gupta and Govindarajan, 2000). Moreover, authors have noted that tacitness, complexity, and specificity are not always beneficial. These attributes can slow learning, and hinder knowledge transfer and recombination within organizations, making it harder for a firm to adapt and thus increasing its vulnerability to innovative rivals (Zander and Kogut, 1995; Szulanski, 1996; Levinthal, 1997; Galunic and Rodan, 1998). The literature provides little guidance for resolving these trade-offs.

In this paper, we investigate whether imitation barriers can protect advantages that stem from unique knowledge. We test this resource-based proposition by examining whether the complexity, specificity, and tacitness of a firm's *technological knowledge* affect the speed with which competitors match its product performance improvements. An *improvement* is any increase in product efficacy

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above and beyond the level of performance previously offered by products on the market, although we distinguish between major and minor improvements according to the degree of advance.

We expect that resource-based predictions for persistence will apply only to *major* product improvements because these, more often than minor improvements, are based on distinctive knowledge. Resource-based theory maintains that if a firm's performance advantage is based on a unique resource, it should persist longer when a firm's rivals cannot easily recreate or gain access to that resource. In our context, competitors must mimic a firm's product design to match its performance, and this requires possession of comparable technological knowledge. Hence, unique knowledge that is better protected by imitation barriers (complexity, tacitness, specificity) should confer more persistent product advantages. By contrast, competitors may find it easier to match incremental improvements because these generally derive from less distinctive knowledge. Consequently, the complexity, tacitness, and specificity (CTS) of the knowledge underlying minor product advantages are unlikely to predict their persistence.

In the remainder of this paper, we discuss the link between technological knowledge and product performance, suggest how CTS can slow knowledge diffusion, and develop arguments for the relevance of imitation for matching major and minor product improvements. We then offer four hypotheses and empirical tests of these, in the context of the adhesives industry. The paper closes by discussing the results, their implications, and areas for further research.

PRODUCT PERFORMANCE AND TECHNOLOGICAL KNOWLEDGE

Most industrial research and development activities have as their aim to determine a product's optimal design parameters, as these are ultimately responsible for its functionality, cost, and reliability (Dixon and Duffey, 1990; Rosenberg, 1994). In addition, although R&D-intensive firms do devote resources to developing basic breakthroughs in scientific knowledge, the bulk of their efforts are focused on the more immediate goals of improving products and processes and developing new ones (Scherer and Ross, 1990; Whitely, Bean, and Russo, 1996). These efforts drive most of the progress that determines how economically significant new technologies become (Enos, 1958; Kline and Rosenberg, 1986). Our focus is on this stage of innovation, improvement within established product categories, rather than on advantages gained by introducing fundamentally new products.

A technological or scientific breakthrough, such as the transistor or Shannon's information theory, is generally followed by a period of highly uncertain R&D in which firms experiment with the best way to exploit the technological and market opportunities it creates (Abernathy and Utterback, 1978; Rosenberg, 1982). This period leads to the establishment of a 'normal configuration,' a set of distinct functions that together constitute the form and determine the operation of a product (Vincenti, 1990).[1] The functions comprising a normal configuration can be represented as a design hierarchy, which depicts the nested relationships among them (Marples, 1961; Clark, 1985). For example, the core function of a copier is the transfer of images. The decision to use an electrostatic transfer process to achieve this function bounds the feasible set of design alternatives for implementing subsidiary functions, such as projection, development of the image, and paper movement (Clark, 1987).

Once a normal configuration is established, a firm improves product performance by using new materials, making structural changes to components, and managing the allocation of functions among components (Vincenti, 1990; Christensen, 1992). Although this stage of innovation has been characterized as incremental relative to breakthroughs, the component and architectural changes that drive product performance vary widely in their magnitude of improvement and the degree to which they require new knowledge (Henderson, 1993). New approaches to implementing functions at the apex of a design hierarchy tend to require more learning, because they alter design choices at each successive level.[2] Also, the higher in a

[1] We use this term, rather than dominant design, which has become somewhat controversial because it presumes that the same configuration is adopted by all firms; we assume only that each competitor stabilizes its particular design approach.

[2] One study found that imitators typically incur between 51 percent and 100 percent of the innovators' development costs for 'major' innovations and between 26 percent and 75 percent for 'typical' innovations (Levin *et al*., 1987). This is consistent with

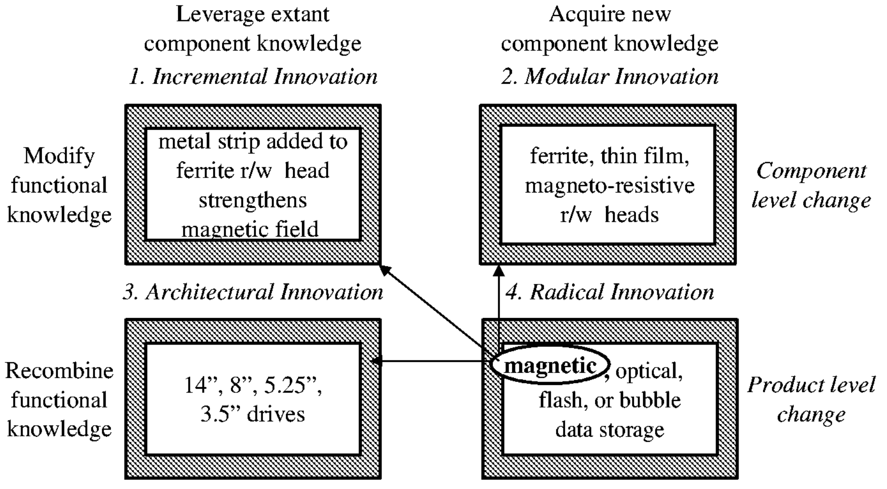

Figure 1. Innovation, technological knowledge, and product performance. (Christensen, 1992)

hierarchy is the function being redesigned, the greater is the potential performance improvement, as these changes alter a larger number of subsidiary design choices. As developers move down the hierarchy, they focus on increasingly fine-grained aspects of component design and less on the fundamental architectural choices that define a product's normal configuration (Clark, 1987).

Henderson and Clark (1990) identify four types of design change that help to describe variation in the degree of new technological knowledge they require, as well as the magnitude of the performance improvements they are likely to generate.

Radical innovation is a design change in a core component or at the top of a design hierarchy (Clark, 1985; Tushman and Anderson, 1986). Magnetic resonance imaging, which partially displaced X-ray technologies used in medical diagnoses, is an example of a radical innovation (Mitchell, 1989; Das and Van de Ven, 2000). Image transfer by X-ray is based on the projection of ionizing radiation into the body, where it is differentially absorbed by tissue. Light and dark images are reflected according to how much radiation is absorbed, and images are captured on film (Office of Technology Assessment, 1984). Magnetic resonance imaging uses a magnet to excite hydrogen atoms in the body; images are obtained by measuring the excitation and relaxation times of these atoms (Office of Technology Assessment, 1984). The components used to transmit and capture images of the body are designed to exploit fundamentally different materials and their properties. Key product functions are allocated among components differently as a result.

Modular innovation also entails changes in the materials and fundamental principles used to design components, but involves functions farther from the apex of the design hierarchy[3] (Clark, 1985; Henderson and Clark, 1990). For example, the read/write heads on magnetic hard disk drives were initially developed using ferrite. Efforts to improve them focused, in part, on reducing the size of the electromagnet embedded in the head (Christensen, 1992). Eventually, the physical limits of these materials prevented further reduction in the electromagnet's size through machining. To advance, firms switched to coating the head with a continuous, thin film of metal, which allowed them to use photolithography to create the electromagnets. These changes required knowledge of new materials, but their fundamental aim was still to exploit the principles of magnetic attraction. Modular innovation is often self-contained whereas a change in a core component typically impacts many subsidiary components.

Incremental innovations are made to maximize the performance potential inherent in a given approach to component design. For example, three

the idea that major improvements embody more new knowledge than minor improvements, which imitators must recreate to successfully replicate major performance gains.

[3] For flat design hierarchies, the critical issue is which components implement most of the functionality in a product or have the greatest implications for peripheral components and their design.

important changes were made in the design of ferrite heads: barium was added to increase strength, allowing heads to be ground finer; 'lapping' processes supplanted grinding to produce smaller heads; and a thin strip of metal was added to the head to strengthen its magnetic field (Christensen, 1992). Firms had to augment their knowledge of how to exploit ferrite to attain these advances. Architectural changes, such as reducing the size of the disk, demand that firms also reconsider how the functions represented in a design hierarchy are distributed among components (Henderson and Clark, 1990). Modular and architectural innovations generate improvements of a magnitude somewhere between incremental and radical design changes (Henderson, 1993).

Thus, scientists and engineers manipulate product performance through the design parameters used to configure and integrate components. To replicate superior product performance, competitors therefore need access to the components that embody these design changes, or knowledge to make comparable improvements in their own products.

Besides engaging in their own R&D, firms can acquire this knowledge through a variety of channels, including reverse engineering, examining patent applications and scientific and trade publications, hiring a competitor's employees, engaging in informal conversations with employees at trade shows or technical meetings, and by communicating with suppliers and customers (Mansfield, 1985; Levin *et al.*, 1987; Appleyard, 1996). Firms sometimes resort to illegal practices, including posing as an employee's coworker over the phone, as an academic at professional meetings, sifting through competitors' refuse for codified technical information, or bribing employees to divulge trade secrets (Carlton, 1992).

These channels are widely used across industries, although the most effective approach for learning varies (Levin *et al.*, 1987). Where reverse engineering is dominant, we might expect characteristics of products rather than a firm's technological knowledge to be the critical driver of imitation speed. However, firms can benefit by gathering knowledge about their competitors' innovations before they are commercialized. R&D activities are ongoing and the earlier a firm collects information about competitors' technical successes and failures, the faster it can adjust its own design objectives and approaches.

Moreover, firms typically rely on several channels for learning, as no one source provides complete information (Norling *et al.*, 2000; Hicks, 1995). Simply observing a firm's design choices is insufficient to fully appreciate their performance implications, which may explain why independent R&D is used in conjunction with reverse engineering (Rosenberg, 1982; Levin *et al.*, 1987). While competitors can observe the configuration of a rival's product, they cannot observe the principles by which it operates (Vincenti, 1990). Collins *et al.* (1982) illustrate how published accounts of a laser technology were insufficient to enable its construction; effective problem solving also required communication among the researchers. Conversation is especially important whenever a design change requires a 'gestalt shift' (Gelwick, 1977). Thus, a firm must possess a certain amount of relevant technological knowledge in order to use information gathered through reverse engineering. The more novel the innovator's design, the more limited the insights competitors will likely draw from reverse engineering, and the more important other channels will likely be.

How can a firm prevent its distinctive technological knowledge from diffusing through these channels to competitors, in order to appropriate greater returns from R&D? Prior research suggests this is a serious challenge, as competitors often acquire detailed data on the operation of new products and processes within a year of their development (Mansfield, 1985). Patents can prevent competitors from using this knowledge to directly challenge a firm, but they are only effective in a few industries (Mansfield, Schwartz, and Wagner, 1981; Levin *et al.*, 1987). Companies can instead seek to lock in their customers by developing complementary service capabilities or to leverage an innovation through lean manufacturing capabilities (Teece, 1986). However, lead time is required for a firm to establish such an advantageous position. Indeed, Cohen, Nelson, and Walsh (2000) found that lead time and secrecy have become much more important mechanisms for appropriating the returns from innovation over the last decade, and are now regarded by most firms as more effective than complementary assets. In the next section, we discuss characteristics of knowledge that may expand this window of opportunity.

IMITATION BARRIERS PROTECTING KNOWLEDGE RESOURCES

Three characteristics of knowledge have been repeatedly linked to the height of imitation barriers: tacitness, complexity, and specificity. These attributes increase 'stickiness'—the costs to transfer knowledge across organizational boundaries and the degree to which it resists identification (Williamson, 1985; Zander and Kogut, 1995; Szulanski, 1996; Galunic and Rodan, 1998; von Hippel, 1998). To the extent they slow the diffusion of a firm's knowledge, these attributes may frustrate competitors' efforts to replicate its product performance.

Complexity is usually defined according to dimensions that increase the difficulty of comprehending how a system (i.e., an organization, organism, device) functions or produces some outcome. Simon (1962) defines a complex system as one that consists of *many unique* and *interacting* elements, which have *equally important* effects on the outcomes produced by the system. Elements are distinct when an individual cannot use the same knowledge to understand them, so increasing the number of unique elements raises the amount of information that must be processed to understand the system's behavior. If each element is equally important to the achievement of a performance outcome, knowing how one element functions reveals very little about how the system as a whole works. In addition, if individual elements are interdependent, then one must understand their joint effects on the performance outcome, and the number of interactions increases geometrically with the number of elements.[4]

Complexity may slow performance replication by obscuring the sources of superior performance, raising the costs of transfer, and increasing the likelihood of imperfect imitation (Dierickx and Cool, 1989). Accordingly, MacMillan, McCafferty, and Van Wijk (1985) argue that competitors find it harder to imitate products when their development relies on a complex set of skills.

[4] A fourth dimension of complexity has also been linked to the difficulty of comprehending a system; that is *dynamism*, or the degree of change in the means–end or cause–effect chains that are used to produce a performance outcome (Wood, 1986). The more frequently the relationships among elements of a system and its performance change, the more difficult the system will be to understand, as new knowledge must be acquired. We don't include this dimension of complexity because it is difficult to disentangle from our dependent variable.

Resources are described as being 'specific' when they are maximally effective in a particular use or when utilized by a particular firm (Klein, Crawford, and Alchian, 1979; Williamson, 1985). Most discussions linking specificity to sustainable advantage have focused on firm specificity, or the degree to which a resource loses value outside of a particular organizational context (Peteraf, 1993). Firm specificity may arise from two sources: a resource is most productive when used in conjunction with complementary resources that are idiosyncratic to the focal firm, or when it is applied to serve a set of end users that is unique to the focal firm. We refer to the former as the *resource specificity* of a firm's technological knowledge and the latter as its *design specificity*. These two facets of specificity are not necessarily correlated. What a firm knows about how to exploit the core component of a product may be more or less specific to the peripheral components it is used with, for example, but a firm may, or may not, use the same set of components to serve all customers for all applications. Specificity may prolong a firm's advantage by increasing the immobility of its distinctive resources (Peteraf, 1993).

Two dimensions of tacitness are discussed in the literature. The first is the *inability to articulate* what one knows about how to achieve an observed performance outcome (Polanyi, 1962; Nelson and Winter, 1982). The *procedures* one relies on may be inaccessible either because they have been learned implicitly or because they have become second nature and are taken for granted or forgotten (Reber, 1993). However, even if the steps a firm follows can eventually be articulated, this may be insufficient for another firm to achieve the same level of performance. For example, competitors may follow the same basic procedures to make pianos or violins, but be unable to achieve quality or product performance that is comparable to that embodied in a Steinway or Stradivarius (Garud, 1997). Experts might subconsciously attend to cues and make judgments that are not communicated or observable.

On the other hand, if the causal mechanisms that influence performance are known, these may be acted on in a variety of ways, so even if a competitor cannot imitate the same procedures, it may be able to replicate the firm's performance. Thus the second dimension of tacitness is the *personal nature* of knowledge (Polanyi, 1962; Nonaka and Takeuchi, 1995), which derives from an inability to articulate the *principles* that affect the level of performance one achieves. Both dimensions describe knowledge that cannot be communicated sufficiently to enable others to reproduce a firm's performance, suggesting innovations based on tacit knowledge will take longer to replicate (Mansfield *et al.*, 1981; Teece, 1986).

IMITATING MAJOR VS. MINOR PERFORMANCE IMPROVEMENTS

Performance advantages based on knowledge that is tacit, complex and specific might be harder to replicate because the causes of superior performance are more ambiguous to outside observers than to members of the focal firm (Reed and DeFillippi, 1990; Barney, 1991). However, barriers to imitation will only explain persistence when imitation is the best way for rivals to close a performance gap. More specifically, CTS will be stronger predictors of persistence to the extent that knowledge flowing through the aforementioned channels is a valuable input to competitors' development activities. We expect a firm's knowledge to be more useful for closing major, rather than minor, performance gaps for three reasons: (i) imitation will usually save a firm more time and expense for major innovations; (ii) competitors have fewer equally effective alternatives to imitation for closing major performance gaps; and (iii) obtaining information about minor improvements may be costlier.

Mansfield *et al.* (1981) found that imitation is the preferred approach for a competitor when research is a large component of the innovator's development budget. Imitation saves a competitor the time and expense of searching for and experimenting with new technologies; however, it does not necessarily reduce the challenges associated with implementing them. Whereas research is often a discretionary activity, the activities needed to bring a new or improved product to market, such as the construction or retooling of production equipment and redirection of marketing and distribution channels, are unavoidable. Provided that a competitor can understand the choices resulting from a firm's research, it need not repeat the same search and experimentation that lead to these choices. Since research tends to be a more important precursor to major (rather than minor) performance improvements, imitation may be a more effective way of closing exceptionally large performance gaps. Moreover, learning from others is more valuable when the number of alternatives a firm needs to consider is large, and it faces a great deal of uncertainty (Levitt and March, 1988; Haunschild and Miner, 1997). The higher in a design hierarchy an improvement is anchored, the more design changes a firm needs to investigate before selecting an appropriate approach.

Second, major improvements are not easily matched by lower-level design changes, but competitors could seek substitute technologies with which to modify core product components. The odds of this producing an equally effective design may be quite low, however, since prior experience is of limited value in explorative search (March, 1991). Moreover, the time lost responding to the innovator allows it to move down the learning curve and raise the performance substitutes must deliver to be competitive. Imitation should reduce the time competitors need to close major performance gaps, compared to the time starting from scratch requires, and it will likely be more reliable than innovating anew.[5] Additionally, Wilson (1977) argues that major innovations are licensed more often than minor ones because a licensee saves fewer of the costs associated with product development for minor innovations. Since minor improvements generally arise from low-level design changes, wherever firms have made different high-level choices, imitation may be impossible.

Finally, the smaller the change to a firm's product composition, the harder it is for a competitor to detect this through normal intelligence-gathering activities. Less information will likely be published (in advertisements or technical papers) about smaller improvements. Design changes responsible for minor improvements are less obvious, so

[5] Levin *et al.* (1987) found that imitators of 'typical' innovations incur a smaller fraction of the innovator's costs than an imitator of 'major' innovations, implying that the benefit (cost savings) of imitation is greater for minor improvements than for major ones. Nevertheless, the *total research expense* avoided through imitation is likely greater for major innovations. Since the required investment in complementary activities needed to commercialize minor or typical improvements is generally less than for major ones, research may, however, be a relatively small *percentage* of the total costs to develop new or radically improved products (Rosenberg, 1994). For minor improvements, avoided research costs would constitute a larger proportion of total development costs, but fewer total dollars are saved than through imitating major improvements.

reverse engineering may not be as efficient. Information gathering may also be harder, as the source of improvement could reside at more places throughout an organization. Small changes require less effort, and as a result they, and the circumstances that made them feasible, may be forgotten. Minor product enhancements will likely receive less attention from customers and suppliers, and hence may not be brought to a competitor's attention through these channels. If a competitor notices that a firm has gained a minor performance advantage, imitation barriers should be less relevant for prolonging it because the competitor can often match these by modifying its own product designs or production processes, without emulating the innovator.[6]

HYPOTHESES

We expect RBV predictions to hold for major performance advantages, as these are generally based on knowledge that competitors have not yet acquired and this enhances the value of imitation. The CTS of an innovator's capabilities will be insignificant predictors of the persistence of minor improvements since competitors have more alternative means of exploiting their own competencies to achieve these, and face greater constraints in implementing competitors' incremental design changes. To relate CTS to the persistence of major performance advantages, we describe how these attributes may slow diffusion of a firm's knowledge through reverse engineering, verbal and written communication, and hiring away employees.

Complexity

Complex technologies take longer to reverse engineer because a greater number of components, and relationships among them, must be examined and their effects on the overall functionality and performance of the product determined (MacMillan *et al.*, 1985; Winter and Szulanski, 1999). Moreover, the more a developer must know about each component (e.g., the number of physical properties that are pertinent to how it can be manipulated to affect product performance) the less information competitors will likely gain from reverse engineering. Complexity makes intelligence gathering difficult because information about product efficacy, development activities, and application procedures must be collected from a greater number of suppliers and employees. Information that is obtained in small fragments will take longer to reconstruct, and there is greater opportunity for error in this process. If their technological knowledge is complex, developers might depend upon the complementary expertise of other employees to fully explain how a product's design generates superior performance. This limits the benefits of hiring individual developers away, and raises the cost of acquiring a firm's technological knowledge. We therefore propose:

Hypothesis 1: The complexity of a firm's technological knowledge will be positively related to the persistence of its major performance advantages.

Tacitness

The more tacit a firm's technological knowledge, the less employees can communicate to suppliers, customers, or their peers, who might deliberately or inadvertently share information with the firm's competitors. If few of the reasons for a product's superior performance can be articulated, competitors only acquire partial knowledge through their intelligence-gathering activities. Also, it is hard for a competitor to assess the true value of an individual's tacit knowledge. Often such knowledge is useful only in the specific context of a firm. Employees that are hired away might be less productive in another firm (Barney, 1992; Arora and Gambardella, 1994; Torrisi, 1998). Thus, we hypothesize:

Hypothesis 2: The tacitness of a firm's technological knowledge will be positively related to the persistence of its major performance advantages.

[6] Christensen's (1992) study of the hard disk drive industry illustrates nicely how heterogeneous competitors' approaches to product improvement can be. Some manufacturers in this industry consistently relied on modular innovation to sustain performance improvement, while others sought to extract as much improvement out of older component technologies as possible, through architectural and incremental innovation.

Specificity

Products supported by highly specific knowledge are challenging to reverse engineer because idiosyncratic features of the application context moderate the relationships between design parameters and product performance. Thus, competitors that lack contextual knowledge will find it difficult to discern the reasons for a product's superior performance. Intelligence gathering is also difficult for competitors unfamiliar with the application. Suppliers are unlikely to possess the detailed knowledge of the application that a firm has, and customers might take the idiosyncrasies of their own needs for granted and fail to communicate them to competitors. Further, there are fewer sources of potential knowledge leak, since each product is designed for a narrow set of customers. While it is possible to hire away key employees, these experts may not apply their specialized knowledge to a competitor's product components and architecture with the same proficiency. Moreover, if a firm's ability to exploit individual components depends heavily on its experience with a set of related components, the firm's technological knowledge will be less useful to competitors. Each firm likely utilizes and understands an overlapping but distinctive set of product components. To the extent a firm's ability to exploit each component depends on knowing how it interacts with an idiosyncratic set of related components, the less valuable it will be to other firms. As long as competitors cannot productively exploit a firm's knowledge, imitation may be delayed. Based on this, we expect:

Hypothesis 3: The specificity of a firm's technological knowledge will be positively related to the persistence of its major performance advantages.

Given our discussion in the previous section, we do not expect the CTS of an innovator's technological knowledge to be significantly related to the persistence of its minor performance improvements. Incremental changes can be difficult to transfer across firms, and competitors frequently have alternative means of achieving the same degree of improvement. Information about minor improvements may be costlier to obtain and generate smaller savings through avoided research expense. As a result, companies are less likely to devote resources to gathering detailed information about the sources of minor improvements. Therefore we expect:

Hypothesis 4: The complexity, tacitness, and specificity of a firm's technological knowledge will not be significantly related to the persistence of its minor performance advantages.

METHODS

Research setting

We tested these hypotheses in the adhesives industry. Adhesives are used in numerous end products, including automobiles, airplanes, medical devices, textiles, footwear, food packaging and labeling, and wood, furniture and paper products (Skeist, 1992). Superior adhesive performance generates cost savings and improves product quality for these manufacturers. New substrates, manufacturing equipment, and changes in the end use or application environment demand that adhesives be reformulated and create opportunities to gain product performance advantages. Product innovation is thus a central focus of competition.

Adhesive performance is almost fully determined by a product's design.[7] Individuals are typically given full responsibility for developing new products and improving them, so that technological knowledge largely resides with a few experts. Employee turnover has traditionally been very low, and experienced formulators are responsible for training new employees in their approach to adhesives design. Consequently, we could measure the knowledge characteristics of firms by studying the design approach of their most experienced formulators.

Data sources

The data for this study were collected using two survey instruments, developed through extensive secondary research and fieldwork. We worked closely with the corporate R&D department of a firm whose primary business is adhesives

[7] Customers may experience somewhat different levels of performance according to their application procedures, but the performance potential embodied in an adhesive, which is measured under controlled laboratory conditions and by following a standard set of test procedures, is determined by design; manufacturing processes have little effect on product performance.

formulation. This firm provided access to key scientists and experienced formulators. We spent several months interviewing these individuals to learn how adhesives are developed, to identify the design choices that affect product performance, and to understand how formulators make these choices. Interview data were validated using trade journals (e.g., *Adhesives Age*), the *Handbook of Adhesives* (Skeist, 1992), and two technology experts, each with over 30 years of experience in the industry.

Technological knowledge

We focused on three adhesives technologies: hot melts, emulsion polymers, and reactives, which account for the majority of adhesive products sold. Each technology can be used to develop products for many applications (e.g., carton and case sealing, diapers, cigarettes), and our dependent variables are at this level. We ask, for instance, how long it typically takes a firm's competitors to match its major and minor performance advantages, when it introduces new diaper adhesives. Persistence at this level is related to attributes of knowledge for technologies (i.e., what a formulator knows about developing hot melts), as our fieldwork suggested that the structure of a formulator's knowledge would be most stable at this level.

A formulator's knowledge has both content and structure. Knowledge content refers to particular facts and theories, which are both inputs to and outputs of the innovation process. Formulators start with an understanding of various components, their physics and chemistry, and how they can be combined to achieve the desired performance. The facts and theories applied to formulation may be reaffirmed, or they may be modified and qualified each time they are used. Knowledge structure, on the other hand, is more inertial and easier to measure. It defines the approach that a formulator takes to solving a performance problem. For example, does he typically incorporate a wide or narrow variety of components in his product design? Does she tend to use new materials (specific to each customer and application) or rely on a shared list? Does he use a fixed recipe for formulating products or tailor them to suit each customer and application? These heuristics are acquired through experience and are quite durable.

We focus on knowledge structure to measure complexity, tacitness, and specificity. Knowledge structures have been typically used to examine how information is organized in memory (Walsh, 1995). *Categories*, groups of objects, events, or phenomena that are perceived to have similar properties are believed to be a particularly important type of knowledge structure (Rosch, 1978; Rosch and Mervis, 1981). To measure knowledge, we identified categories of understanding that a formulator uses to manipulate adhesive performance.

The innovation literature suggests that such knowledge is organized into two categories: product components and architectural design choices (Laudan, 1984; Henderson and Clark, 1990; Vincenti, 1990). Each adhesive technology is associated with a unique set of components, which are distinguished according to functions such as tackifying, plasticizing, or catalyzing. The design choices that formulators make are what *types* of components to use, and *what variety* of each component to use, where the latter refers to organic and inorganic substances that can perform a particular function (e.g., silica and clay could both act as a tackifier). The *amount* of each component to use is also a critical design choice.

To make these design choices, formulators either recall which component varieties have worked in the past or they remember which *physical properties* of components are responsible for its effects. Thus, components' physical properties also constitute an important category of technological knowledge. These four knowledge categories—component types, varieties, amounts, and physical properties of components—formed the basis of our survey measures of knowledge attributes. Specifically, we measured knowledge attributes by asking a firm's experts about their abilities to exploit understanding in these four areas to affect product performance.

Independent variables

Complexity

To measure complexity, we created a matrix with six product performance criteria across the top and a list of components (all those relevant to a particular technology) down the left-hand side. We verified through our pretests and field interviews that these six criteria—adhesion, strength, ease of application, open time/set speed, stability, and aging—were the most fundamental measures of performance for any adhesive product. The component list for each technology differed; firms received surveys that correspond to the technologies they use.

Respondents were asked to focus on each performance criterion in turn and, for each, to rank the components according to their importance for influencing that criterion. Any components that a firm does not use were left blank, so these rankings indicate both the number of components used to affect product performance and the equality of their importance. A concentration ratio was computed for the set of components used to influence each of the six performance criteria. We then took the average of these six concentration ratios and subtracted it from one to obtain a measure of complexity, following Dess and Beard (1984).[8]

Specificity

We developed two measures of the specificity of technological knowledge. *Resource specificity* captures the extent to which what a firm knows about product components is specific to a customer, application, or component varieties. For example, a firm might learn that a physical characteristic of tackifiers, such as molecular weight, affects the open time/set speed of adhesives. Alternatively, the firm might know from experience that certain tackifiers slow open time/set speed when used in a particular context or in conjunction with certain backbone polymers. However, even a firm with general knowledge of the components it uses might formulate unique adhesives for each application. Therefore, we also measured specificity as *design specificity*, or the extent to which a firm acquires specialized architectural knowledge by tailoring its adhesive formulas for individual customers and applications.

[8] Although there is variation among components in the extent to which they interact with other components to affect the six performance criteria, our pretests and interviews suggested that this is not a distinguishing characteristic of a formulator's design approach. It tends to be a byproduct of the components a formulator uses for a specific product, which affects the amount of each component used, rather than something formulators deliberately and consistently try to build into or avoid in their products. Therefore, we do not measure interdependence as a dimension of the complexity of a firm's technological knowledge.

Tacitness

Irrespective of their experience level, engineers often rely on an intuitive understanding to solve design problems (Laudan, 1984; Vincenti, 1990). The knowledge employed in this process is tacit when an engineer cannot fully explain which parameters are responsible for changes in performance (Polanyi, 1962; Bohn, 1994). An expert's knowledge might be tacit because problem solving has become second nature, and causal relationships have effectively been forgotten (Wagner, 1987). A less experienced person might also achieve superior performance without yet being conscious of the causes (Reber, 1993).

Engineers that know which design parameters affect which performance outcomes, and why, should be better able to communicate the source of a firm's advantage (Cowan and Foray, 1997; Torrisi, 1998). Therefore, we measured tacitness as the inverse of a formulator's ability to *explain* and *predict* the relationships between components, design choices, and product performance. Knowledge that cannot be verbalized remains tacit. If a formulator cannot predict what she needs to do to manipulate product performance, this indicates a lack of causal understanding. Table 1 contains an abbreviated version of the survey items.

Dependent variables

Adhesives manufacturers routinely engage in incremental, modular, and architectural innovation, as depicted in Figure 2. These product changes yield fairly small performance improvements. Major performance improvements are typically gained by using a new backbone polymer, a radical design change, and adjusting the peripheral components accordingly. Introducing a different adhesive technology for a particular application (e.g., a reactive where hot melts were previously dominant) can also confer a major performance advantage.

Because we could not track the individual design changes firms have made over time, we distinguish advantages according to the degree of performance improvement. We defined a *major improvement* as one that: (1) offers customers *substantially higher performance* (e.g., better machinability) than existing versions of a product, or (2) embodies a *new combination of performance characteristics* (e.g., flexibility and a superior set rate) that existing products do not offer. A new product may also

Table 1. Sample survey items

Resource Specificity

Knowing how the *physical properties* (e.g., molecular weight, T_g) of this backbone polymer affect adhesive performance can help us to manipulate the same properties of other backbone polymers to improve adhesive performance.

Knowing how one *type of component* (e.g., thickeners) affects adhesive performance when they are combined with *this backbone polymer* can help us determine how to use those components with other polymers.

Design Specificity

We exploit the same *physical properties* of this backbone polymer (e.g., molecular weight, T_g) to enhance a given adhesive performance criterion (e.g., strength), regardless of the application.

We use the same *component varieties* (e.g., silica as a thickener) to improve adhesive performance, regardless of the application.

Tacitness

We can predict which *varieties* of a component (e.g., esters or alkyd resins as plasticizers) to use to improve adhesive performance.

We can predict *how much* of a particular component to use to improve adhesive performance.

We can explain why using certain *varieties* of component results in specific adhesive performance characteristics.

We can explain why using certain *amounts* of component results in specific adhesive performance characteristics.

Complexity

1. Adhesive Components	2. Ease of Application	3. Open Time/Set Speed	4. Adhesion	5. Stability	6. Strength	7. Aging
a. Backbone Polymer	______	______	______	______	______	______
b. Functional Groups	______	______	______	______	______	______
c. Plasticizers	______	______	______	______	______	______
d. Viscosity Modifiers	______	______	______	______	______	______
e. Tackifiers/Extenders	______	______	______	______	______	______
f. Fillers	______	______	______	______	______	______
g. Stabilizers	______	______	______	______	______	______

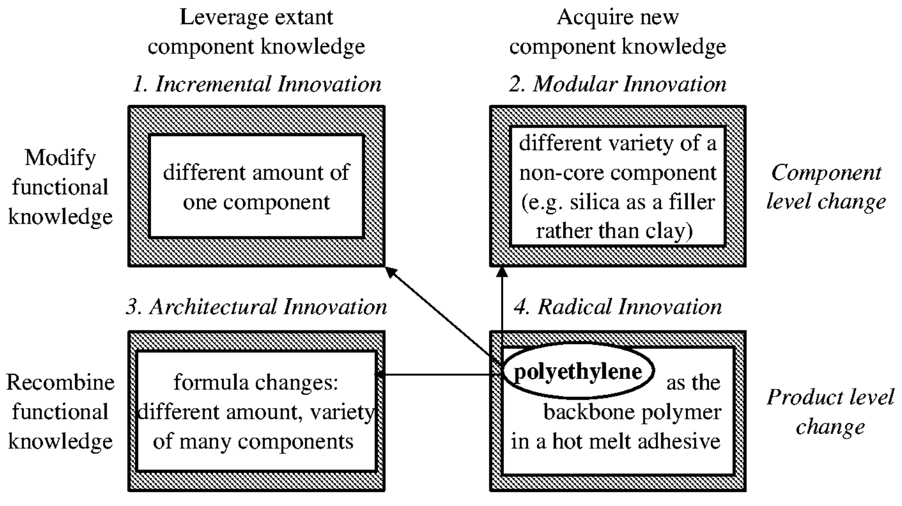

Figure 2. Innovation and technological knowledge in the adhesives industry

Table 2. Simple correlations

	Tacit	Resource specific	Design specific	Complex	Variety	Leadership	Mos. to imitate	Mos. to develop	Persist. radical
Resource Specific	0.34 (0.0001)								
Design Specific	0.39 (0.0001)	0.07 (0.42)							
Complex	−0.37 (0.0001)	0.11 (0.21)	−0.03 (0.75)						
Variety	0.03 (0.73)	0.03 (0.74)	−0.16 (0.06)	−0.20 (0.01)					
Leadership	−0.26 (0.001)	−0.25 (0.002)	−0.05 (0.52)	−0.06 (0.47)	0.07 (0.39)				
Months to imitate	0.06 (0.46)	0.20 (0.02)	−0.13 (0.12)	0.13 (0.13)	0.26 (0.002)	0.07 (0.38)			
Months to develop	−0.03 (0.72)	0.26 (0.002)	−0.22 (0.002)	0.07 (0.38)	0.09 (0.29)	0.04 (0.61)	0.76 (0.0001)		
Persistence—radical	0.13 (0.12)	−0.005 (0.95)	0.07 (0.43)	0.10 (0.21)	0.29 (0.0004)	0.06 (0.47)	0.62 (0.0001)	−0.03 (0.69)	
Persistence—incremental	−0.23 (0.003)	−0.27 (0.0004)	0.12 (0.14)	0.01 (0.89)	0.04 (0.59)	0.43 (0.0001)	0.07 (0.38)	−0.03 (0.70)	0.17 (0.04)

enable (3) *customers* that could not use existing products *to use a newly introduced version*. An improvement that qualified on at least one of these dimensions, when compared with products previously on the market, was considered major.

The advantage that a firm derives from its distinct technological knowledge will persist until competitors are able to achieve equivalent product performance. Therefore, we measured persistence as *Months to Imitate*, or the number of months it typically takes competitors to replicate major performance improvements. We asked respondents to refer to their three largest application areas (by sales revenue) for a given technology when providing responses for this dependent variable.

The pretest suggested that an estimate in weeks or months would not be reliable for minor improvements because there is tremendous variance in the time required for small design changes. However, formulators were comfortable judging whether competitors tend to replicate minor advantages in more or less time than they took to develop. Therefore, we measured the persistence of minor advantages (*Persistence—Minor*) using two 7-point Likert scale items. The items ask whether it usually takes competitors longer to replicate a firm's product improvements than it takes the firm to develop them; the second item is worded in the reverse fashion.

We constructed a second measure of persistence for major improvements, *Persistence—Major*, so that we could compare how complexity, tacitness, and specificity affect the sustainability of major and minor advantages. This measure adjusts Months to Imitate for a firm's own development time, in the same way the items for minor improvements do. A comparison of columns 2 and 3 in Table 2 suggests that development time affects persistence in the same way whether it is included as an independent control variable or is factored out of Months to Imitate.

Control variables

Variety controls for the existence of competitors who compete with different technologies (emulsion, hot melt, or reactive). Competitors might find it harder to imitate a firm's innovations if they use a different technology. On the other hand, if these technologies are close substitutes for one other, competitors may be able to match a firm's performance quickly without having access to its knowledge. *Leadership* controls for the frequency with which a firm introduces innovations ahead of its competitors. A firm that is always a leader in innovation might attract attention and become a benchmark for competitors, and if competitors recognize its innovations faster, this would reduce persistence. However, by continually emphasizing leadership in innovation, a firm may become more competent in exploiting a particular technology, enabling it to consistently develop new products in less time than their competitors.

We use *development time* as our third control variable. Without this control, we might conclude that a 6-month imitation lag (for product A) is 'better' than a 1-month imitation lag (for product B). This would be inaccurate if it takes only 2 weeks to develop product B, but 6 months to develop product A. The firm selling product B probably requires much less time to recoup its development costs, and likely has a very different time frame in mind when it targets 'sustainable' performance advantages. Similarly, if two firms within the same market maintain superior performance for 3 months each, but one develops products in half the time of the other, the firm with speedier development is likely to earn more in the 3 months it sustains superior product performance. Therefore, we control for development time in our first test of resource-based theory, and then measure persistence as the difference between a firm's development time and the speed with which competitors replicate its performance.[9]

RESULTS

Sample size and response rate

We identified a population of 416 firms that formulate adhesives using at least one of the three technologies for this study.[10] Of these, we received

[9] We also controlled for the degree to which a firm patents its products and the amount of experience it has with the technology and in the application. These variables were not significant. As using them slightly reduces the sample size, we report our findings without these controls.

[10] We relied on *American Business Disc*, *Ward's Business Directory*, *Standard & Poor's Register of Corporations and Executives*, *Dun and Bradstreet's Million Dollar Directory*, *Adhesives Age*, and *Adhesive Digest* to identify the population of firms that formulate adhesives. These sources collectively yielded a list of 1329 firms. We called each firm in order to ask for the name of their R&D Director, and to verify which technology(ies) they develop, as well as their mailing address. Of these, 913 firms

surveys from 82 firms, or 20 percent of the population. Five of these firms did not provide us with estimates for the dependent variables. To enhance the reliability of our data, the survey asked whether the firm usually knows when competitors have matched its product performance, in a particular application, and whether the firm is usually aware of how well its products perform relative to those of its competitors. Fourteen of the respondents indicated that they did not track this information very closely, so we did not include them in our sample.

The hypotheses were tested with the remaining 63 firms, although the results do not change substantively when all 77 respondents with full data are included. The firms in our sample provided information for one to three distinct applications, bringing usable observations to 141. We compared the firm size, technologies, and applications covered in our sample with the industry as a whole and found the sample to be representative. There is also substantial variance in the degree to which firms in our sample invest in R&D, introduce new products, and in their financial performance. Thus, we expect the results are unaffected by nonresponse bias.

Validity and reliability

To assess the content validity of our measures, we pretested the instrument with nine experienced formulators in our facilitating company, and with two outside technology experts. Our interviews with these individuals assured us that we had identified all product components and key design choices for each technology. Several of the experienced formulators and R&D managers that we subsequently spoke with over the phone remarked that they found the survey to be extremely thorough in this regard, which further enhanced our confidence in the instrument.

We took steps to reduce nonrandom error associated with our measurement approach (Schwab, 1980; Spector, 1987). Data for the dependent variables were collected using a second survey, which we sent 6 weeks after receiving a firm's survey for technology characteristics. A third of the data for our dependent variables was gathered by telephone. We did request a different respondent for the dependent and independent variables; however, only four of the firms in our sample were able to comply. Although five of the measures use a Likert scale, the items employ very distinct wording and scale anchors. Our fieldwork suggests that responses are unlikely to be influenced by implicit theories about sustained advantage; none of the people we interviewed mentioned knowledge attributes when discussing product imitation. These factors should reduce correlation among dependent and independent variables attributable to the method used (Podsakoff and Organ, 1986; Phillips and Lord, 1986; Crampton and Wagner, 1994; Doty and Glick, 1998).

Table 2 provides a simple correlation table for the variables in our study. We conducted exploratory and confirmatory factor analyses to evaluate discriminant validity. The items for each attribute loaded cleanly on separate factors, and the goodness of fit indices (estimated with LISREL 8.2) are all above the recommended levels.[11]

The interitem reliability for our measures, according to Cronbach's alpha, is acceptable (Cronbach, 1951). The alpha for Tacitness is 0.93, it is 0.75 for Design Specificity, 0.79 for Resource Specificity, and 0.89 for Complexity. Interrater reliability would help to assure that our attribute measures are representative of the firm's knowledge. Unfortunately, it was not feasible to obtain multiple respondents because many firms are small and our survey is rather lengthy. On the

were eliminated because they either do not formulate adhesives, or do not use one of the three technologies that we focused on. More than half of the firms listed in the adhesives and sealants industry actually make products that are technologically similar but have a distinct function, especially coatings, sealants, caulk, and film products. Other firms were involved in adhesives but not as formulators; some apply adhesives to tapes, distribute adhesives, or make glue-dispensing equipment, while others mix adhesives according to specifications given to them by their customers but do not formulate adhesives.

[11] The goodness of fit measures for the confirmatory factor analysis were as follows. For the tacitness measurement model, the goodness of fit index is 0.94, the adjusted goodness of fit index is 0.89, the normed fit index is 0.95, the comparative fit index is 1.0 and the standardized root mean square residual is 0.035. In the complexity measurement model, the goodness of fit index is 0.98, the adjusted goodness of fit index is 0.94, the normed fit index is 0.98, the comparative fit index is 1.0, and the standardized root mean square residual is 0.028. The design specificity measurement model achieved a goodness of fit index of 0.91, an adjusted goodness of fit index of 0.81, a normed fit index of 0.82, comparative fit index of 0.89, and a standardized root mean square residual of 0.075. For the resource specificity measurement model, the goodness of fit index is 0.97, the adjusted goodness of fit index is 0.93, the normed fit index is 0.96, the comparative fit index is 1.0 and the standardized root mean square residual is 0.04. The minimum fit function, chi-square statistic is nonsignificant for each model, as is desired.

Table 3. Regression results

	Dependent variable: Months to Imitate		Dependent variable: Months to Imitate–Months to Develop	
	Robust std. errors	Negative binomial	Major improvement	Minor improvement
Development time	0.78^{***}	0.60^{***}		
Complexity	0.17^{*}	0.60^{*}	0.27^{*}	0.07
Tacitness	0.21^{*}	1.06^{**}	0.34^{*}	-0.25^{*}
Resource specificity	-0.15^{+}	-0.67^{*}	-0.24^{+}	-0.10
Design specificity	0.01	0.04	0.03	0.23^{*}
Variety of technologies	0.17^{+}	0.19^{*}	0.27^{+}	0.03
Leadership in innovation	0.08^{+}	0.52^{**}	0.13^{+}	0.35^{**}
Goodness of fit measures	$R^2 = 0.68^{***}$	Wald $\text{chi}^2 = 175.94^{***}$ Likelihood ratio $= 46.77^{***}$	$R^2 = 0.17^{***}$	$R^2 = 0.26^{***}$

$^{+}p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

other hand, according to our telephone interviews, most of the firms in our sample rely on one or two formulators to apply a technology to a particular application. Thus, we believe our respondents provide an accurate portrayal of the firm's technological knowledge. Our emphasis on the structure rather than the content of knowledge should enhance the stability of the attribute measures (test–retest reliability).

The models

We first estimated regression models to test the proposition that more durable advantages are likely to stem from knowledge that is complex, tacit, and specific, for major improvements. The variance inflation factors and condition indices for this model were well below the levels that would indicate multicollinearity. We examined Cook's D and the DFBetas to determine whether the results are overly influenced by any observation. Four observations were slightly above the suggested threshold of 0.5 for Cook's D and 1 for the DFBetas (Neter, Wasserman, and Kutner, 1990). The significance of our results increases when these observations are removed, but the results do not change substantively. There is nothing obvious about these products that would make them unsuitable for this study, so they remain in the sample.

The chi-square Cook–Weisberg test statistic for heteroskedasticity is 7.84, which may be due to nonindependence among observations from the same firm. We estimated the robust or Huber/White-corrected standard errors to adjust the standard errors for group-specific variance (White, 1980; Rogers, 1993). These estimates represent a test of Hypotheses 1, 2, and 3 and are presented in column 1 of Table 3.

Normality tests revealed that *Months to Imitate* is positively skewed. Although OLS produces unbiased estimates for non-normal distributions, they will be inefficient and statistical tests can be inaccurate. Months to Imitate can be treated as an event count, which typically takes on a Poisson distribution (King, 1988). However, our data are overdispersed, so negative binomial regression is appropriate (Hausman, Hall, and Griliches, 1984). The second column in Table 3 reports these results. We allow the degree of dispersion to vary randomly across firms, as unobserved firm-specific factors or firm-specific measurement error can affect dispersion (Hausman *et al.*, 1984). The independent variables are logged to maintain the linear relationship suggested by our theory.

To test whether complexity, tacitness, and specificity affect the persistence of minor advantages differently from the way they affect major improvements, we had to transform this model. Our dependent variable for minor improvement is the difference between a firm's development time and imitation speed. To create the analog for major improvements, we subtracted Months to Develop from Months to Imitate. Both *Persistence—Major* and *Persistence—Minor* were normally distributed, so we used OLS to estimate these models. The models meet all of the OLS assumptions, once dependence among observations from the same firm is controlled for. The results are reported in Table 3.

DISCUSSION

Overall, our results support the theoretical claim that attributes of knowledge can prolong performance advantages, and suggest that their value as imitation barriers depends upon the size of a firm's advantage. Complexity and tacitness protect large performance gains, but complexity does not affect, and tacitness negatively affects, the persistence of small leads. The results for major improvements are consistent with studies linking the complexity of new technologies (Rothwell, 1978; Ounjian and Carne, 1987) and their ambiguity (Rogers, 1995; Szulanski, 1996) to a slower rate of diffusion. Similarly, Rivkin (2000) demonstrated that imitating complex strategies is harder and imperfect imitation carries greater liabilities.

Contrary to our predictions, we found a significant negative relationship between tacitness and the duration of minor advantages. We predicted no relationship because we expect firms primarily seek to replicate small improvements through internally focused development initiatives, rather than through imitation. Hence, any effect CTS has on knowledge diffusion would be irrelevant to sustaining incremental leads. However, if these attributes affect capabilities for innovation, they might disadvantage a firm facing innovative rather than imitative competition. For example, the ability to make even minor improvements may require articulable, causal understanding of the relationships between product components and performance outcomes (Winter, 1994; MacDuffie, 1997). A firm that lacks such knowledge would then quickly lose minor advantages to competitors that understand the technology better.

Complexity also slows product improvement in some industries (Vassilikas, 1997; McEvily and Pil, 2001), but can expand opportunities for innovation in others (Fleming and Sorenson, 2001), affording competitors more latitude in replicating minor improvements through substitute design changes. In the adhesives industry, comparable performance can be attained through a variety of different component combinations, which puts it in the latter category. This might explain why we did not find a negative relationship between complexity and the duration of minor advantages. A firm with a more complex approach to developing certain products is not necessarily slower to generate improvements if complexity expands its design options.

On the other hand, design specificity appears to prolong minor advantages. Again, we predicted no relationship, as we expect firms to rely on imitation to replicate small improvements less often than they do for major improvements. However, design specificity may discourage competition if it locks in customers or raises the costs of incremental improvement. Both are possible in this industry. To tailor adhesives, a firm needs to acquire some knowledge that is idiosyncratic to individual customers or applications. As this knowledge is less fungible, tailoring adhesives is riskier. Customers incur some risk to try other products because adhesives can interact unpredictably with the physical characteristics of substrates, equipment, and ambient conditions. Although the investment to experiment with and retool the application process is usually minor, the lost production time may be sufficient to discourage switching for small gains. As a consequence, a firm that designs adhesives specially for individual customers may face fewer rivals during periods of incremental advance than a firm whose product performance is based on more general knowledge of the application environment.

The negative relationship between resource specificity and the persistence of major improvements is perhaps the most surprising and difficult to explain. It may be that having more specific resource knowledge is correlated with introducing relatively smaller major improvements, which are easier for competitors to replicate, as specificity makes it harder for a firm to deviate from its prior experience. Future studies could investigate whether firms that possess knowledge with certain attributes systematically engage in different types of innovations.

We also found that firms introducing major improvements into markets where competitors use a variety of technologies gain more sustainable performance advantages. However, the variety of technologies is not a significant predictor of persistence for minor advantages. This is consistent with the idea that competitors are less likely to copy small product improvements. If imitation were the dominant response, technological homogeneity would make this easier, and we should find a negative relationship between variety and persistence, as we did for major innovations. The results show firms that consistently introduce new products ahead of their competitors are better able to sustain both minor and major performance advantages. This parallels Zander and Kogut's (1995) results and suggests that continuous innovation widens the competence gap between a firm and its competitors.

Collectively, these results support the RBV contention that imitation barriers are at least partially located in resources, and indicate that the theory can be applied to knowledge resources. This does not necessarily mean, however, that managers *should* seek to increase the CTS of their technological knowledge. These attributes can make achieving other objectives, which also affect long-term profitability, more difficult. For instance, a firm might wish to transfer the knowledge it acquires through R&D to other parts of its organization, and this will likely cost more and take longer if the resulting knowledge is highly complex, tacit, or specific (Zander and Kogut, 1995; Szulanski, 1996). Alternatively, a firm may seek to maximize its life chances by developing highly adaptive competencies, yet CTS have been associated with rigidity (Peteraf, 1993; Montgomery, 1995; Levinthal, 1997; Teece, 1998b). These tensions suggest that we need to consider how knowledge-based advantages relate to a firm's other performance objectives in order to offer sound guidance on knowledge management.

Additionally, while our results indicate that knowledge attributes *can* create imitation barriers, they cannot be taken as evidence that such barriers are always the most important factor underlying sustained advantage. Some of the firms we spoke with sell adhesives to a few customers, such as utilities or the government, with whom they have long-term exclusive contracts. Imitation speed in such markets is heavily influenced by the need to fulfill complicated testing and contracting requirements. Our interviews suggest that we also need to take a closer look at how knowledge and physical resources complement one another. Some companies mentioned that even if a competitor introduced new adhesives that it had the technical competence to emulate, it might not respond if it lacked the capital equipment needed to manufacture them. This comment is consistent with the idea that sustainable competitive advantage ultimately stems from bundles of resources and capabilities (Porter, 1996). That said, we believe it is also useful to focus on knowledge as a distinctive source of certain performance advantages. Our results suggest avenues for continuing this inquiry.

To gain further insight into the dynamics of knowledge-based advantage, the present study could be replicated using direct measures of the magnitude and nature of technological change underlying individual performance improvements, or innovations. The hypotheses presented here could then be tested as moderating relationships, allowing for better specification of their functional form. It is possible that complexity and tacitness are only beneficial for extremely large improvements in performance; alternatively, these attributes could be valuable for all but the most minor improvements. Our data do not allow us to determine how big an improvement must be before complexity and tacitness delay imitation. Such data would also enable studies to investigate whether CTS affect a firm's ability to introduce major improvements *and* subsequently lead in developing smaller product enhancements. Another empirical strategy would be to investigate directly whether CTS influence the efficacy of various channels (e.g., reverse engineering, communication) for learning about competitors' technologies.

To assess the generalizability of our findings, studies should investigate how barriers to knowledge diffusion operate in industries where other functions, such as manufacturing and technical service, make important contributions to product performance. These functions might contribute to performance in ways that are difficult to extract through reverse engineering, raising the value of knowledge barriers. Reverse engineering food products, for instance, can reveal key ingredients, but not how a product was produced (e.g., the order ingredients were added, speed at which they were mixed, temperature). Manufacturing processes critically affect the composition, quality, and performance of many products.

We focused on knowledge used to manipulate product performance, but other competencies shape a firm's ability to transfer this knowledge or apply it in new ways. A strong grasp of scientific principles (e.g., of adhesion, materials science, rheology) may facilitate the transfer of more tacit, application specific knowledge (Torrisi, 1998). If competitors possess abstract, general understanding, even a firm's tacit knowledge could diffuse (Cowan and Foray, 1997). In addition, the effects of certain attributes are still subject to debate. Whereas Galunic and Rodan (1998) suggest tacitness may frustrate innovation, Hedlund (1994) argues that tacitness, to the extent it reflects less formalization and codification of knowledge, may foster creativity. Complexity has also been linked with both opportunities for and difficulties associated with innovation (Fleming and Sorenson, 2001; Sanchez and Mahoney, 1996). Such contradictions might be resolved by studying the interplay among complementary bodies of knowledge.

CONCLUSION

Resource-based theory maintains that intangible resources, such as knowledge, are especially likely to confer sustainable competitive advantage (Wernerfelt, 1984; Barney, 1991). Yet, we know very little about *how* knowledge-based advantages are sustained (Teece, 1998a). One possibility is that certain types of knowledge diffuse slowly. Another is that knowledge is a more fungible resource and hence is less likely to depreciate as conditions change (Teece, 1980; Lado and Wilson, 1994; Miller and Shamsie, 1996). We provide evidence on the former proposition. Specifically, this study has examined resource-based hypotheses about sustained advantage by focusing on technological knowledge, directly measuring the attributes believed to slow its diffusion, and relating these to the persistence of product performance advantages. Overall, the results support the RBV contention that imitation barriers are at least partly located in resources, and suggest that the theory can be applied to knowledge resources. However, we also offer several qualifications to the theory—the most important being that the size of a firm's advantage may moderate the efficacy of these barriers.

The challenges associated with measuring knowledge and barriers that protect it from imitation are a central reason for the lack of empirical studies testing RBV's predictions. This study offers an approach for addressing these challenges. First, a key difficulty associated with empirically validating resource-based theory is identifying unique resources. At least part of the knowledge underlying any innovation is idiosyncratic to the firm, and its distinctiveness likely varies with the magnitude of improvement (McGrath *et al*., 1996). This makes organizational and technological innovations a good focal point for researching RBV. Second, the link between resources and rents is usually not a direct one, except when resources are fortuitously procured. We focused on intermediate performance outcomes, which mediate the link between resources and rents, because understanding these competitive dynamics is crucial for discerning conditions for persistence. Research at this level could help to determine when preventing imitation vs. facilitating innovation is a more important precursor to sustained advantage.

Finally, knowledge is an especially difficult resource to measure because of its fluidity. Previous studies have mainly used proxies for stocks of knowledge, on the assumption that firms acquire more knowledge about activities they invest or engage in to a greater extent. While sufficient for many purposes, these proxies are not easily linked to the specific barriers to imitation discussed in the RBV literature. To get around this, researchers have typically offered qualitative evidence to illustrate the tacitness or complexity of knowledge. This study shows there can be substantial variation in the CTS of a body of knowledge across firms. We suggested knowledge can be measured by identifying stable categories of understanding, which are relevant for affecting some outcome, and that these can be used as the basis for constructing attribute measures. Zander and Kogut (1995) employed a similar approach to assess the complexity of manufacturing capabilities. Researchers might also use this method to measure firm specificity as the rarity of categories used to affect specific performance objectives.

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