Into the Black Box: The Knowledge Transformation Cycle

Paul R. Carlile • Eric S. Rebentisch
Sloan School of Management, Massachusetts Institute of Technology, E52-567, Cambridge, Massachusetts 02142
Center for Technology, Policy, and Industrial Development, Massachusetts Institute of Technology, 41-205, Cambridge, Massachusetts 02139
carlile@mit.edu • erebenti@mit.edu

This paper examines how knowledge is integrated in complex technology and product development settings. By framing the task of knowledge integration as a cycle, we highlight the inability of current knowledge transfer theories to explain the consequences that arise from the path-dependent nature of knowledge. We compare the complexity of this knowledge integration task to previous efforts in terms of its novelty and the organizational properties of specialization and dependence that are required. Drawing on evidence from two empirical studies, we outline three stages of the "knowledge transformation cycle," which addresses the complexity of this integration task. We conclude with the implications of this knowledge transformation cycle on our understanding of knowledge management and organizational learning.
(*Knowledge Transfer; Boundary Spanning; Organizational Learning; Product Development*)

1. Introduction

Firms of even moderate size and scope must address the problem of integrating contributions from multiple specialty areas. Moreover, firms are beginning to appreciate the benefits of close interactions with suppliers, partners, and customers throughout the value stream. The currency of these interactions and communication is information, at the least, and more likely complex forms of specialized knowledge. As the scale and scope of the integration task increase—perhaps as a result of product complexity, technical advances, or the difficulty of the regulatory environment—a firm's effectiveness in knowledge integration (Grant 1996) will distinguish it from its competitors.

This strategic requirement exposes the challenge of integrating knowledge across the boundaries created by specialized knowledge domains. Knowledge transfer is a growing area of the literature that is relevant to the task of knowledge integration across these boundaries; it explicitly examines the movement of knowledge from one group to another (Argote 1999, Szulanski 2000). The path-dependent nature of knowledge presents a challenge that has not yet been fully addressed by the knowledge transfer and knowledge integration approaches. When new demands fall within the domain of the firm's past activities, the firm's knowledge may be a source of competitive advantage. When new demands fall outside the domain of the firm's past activities, the firm's knowledge may become a competency trap (Levitt and March 1988) or even a source of rigidity (Leonard-Barton 1995).

In what follows, we discuss the sufficiency of a knowledge transfer approach by addressing the questions that arise when knowledge transfer is operationalized as a cycle. By framing the repeated process of knowledge transfer as a cycle, we gain fundamental insights into the challenges of integrating knowledge in firms. Some literature does

Management Science © 2003 INFORMS
Vol. 49, No. 9, September 2003, pp. 1180–1195

0025-1909/03/4909/1180
1526-5501 electronic ISSN

acknowledge the challenges that path dependency generates from a knowledge transfer approach (Hargadon and Sutton 1997), but the consequences of this cycle have not been adequately addressed. We compare the complexity of knowledge integration to previous efforts in terms of its novelty and the organizational properties of specialization and dependence that are required. We draw on evidence from two empirical studies to describe a "knowledge transformation cycle" that addresses questions unanswered by previous theories. We then outline the three stages of the knowledge transformation cycle and the value it adds to the task of knowledge integration. We conclude with the implications of this transformation approach on research and practice relating to organizational learning and knowledge.

2. Knowledge Integration

A core challenge of any organization is to create new knowledge (i.e., solutions to problems, new products, etc.) through the integration of knowledge from different sources. The study of knowledge transfer is an important area of prior research that supports this inquiry because the movement of knowledge from one location to another is central to integration activities. Argote and Ingram (2000, p. 152) define knowledge transfer as "the process through which one unit (e.g., individual, group, or division) is affected by the experience of another." This working definition is consistent with much of the knowledge transfer literature and its empirical focus on understanding the transfer of knowledge from an "expert" site to a "novice" site. One body of research on learning curves (Argote et al. 1990, Epple et al. 1991) examines factors (e.g., geographic distance, production rate) that constrain the movement of expert knowledge in both intra and interfirm large-scale production contexts. Other research examines the transfer of knowledge across franchise-based service firms (Darr et al. 1995) and finds that where there is greater similarity between stores (i.e., common ownership, geographic location), knowledge transfer is more successful. Szulanski (1996) identifies that increasing stickiness of knowledge created barriers in transferring "best practice" from one site to another in a firm.

While these studies have been useful in describing movements of knowledge from expert sites to novice sites, some researchers in the knowledge transfer domain have focused on knowledge transfer as a repeated process. Hargadon and Sutton (1997) summarize a process model of knowledge transfer based on organizational learning and memory perspectives (Huber 1991, Walsh and Ungson 1991) that includes the stages of acquisition, storage, and retrieval. In this model, knowledge is acquired from external sources via organizational search routines, stored in organizational memory (e.g., in people's minds and organizational routines; Nelson and Winter 1982), and retrieved from organizational memory for use.

Linking knowledge storage (retention) and retrieval implies a repeated cycle and, further, that knowledge transfer can have a positive or a negative effect on succeeding cycles. The effects of the cyclical nature of knowledge transfer have been described in the literature of organizational memory (March and Simon 1958, Walsh and Ungson 1991) and organizational learning (March 1972, Huber 1991, Hargadon and Sutton 1997) in terms of the path-dependent nature of knowledge. However, the full implications of this path dependence have not been sufficiently addressed in the knowledge transfer literature to date. Furthermore, the underlying mechanisms or processes that resolve the negative consequences arising from the cycle have not been adequately explained by the use of broad labels such as "adaptation." They remain, essentially, a "black box."

Given the acquisition-storage-retrieval cycle, how well storage is performed can impact the efficacy and/or the relevancy of what is retrieved. March (1972, p. 427) asserts that, for the most part, "good memories make good choices." However, bad choices can also be made even from good memories if the circumstances surrounding the original development have changed. In such cases, stored knowledge is no longer relevant and can prove problematic when it is retrieved for reuse. This is a key point: When the context changes (i.e., new requirements or novel conditions arise) between when knowledge is stored and when it is retrieved, the usefulness of the stored knowledge decreases, and it can even become harmful. Thus, *the amount of novelty introduced between* *knowledge storage and retrieval* is a core knowledge integration challenge.

This knowledge integration challenge becomes more problematic when we realize that current frameworks of knowledge transfer and integration do not apply with equal explanatory power to both simple and complex knowledge integration tasks. Complexity can be defined as a whole that is made of interrelated parts. Interrelationships, or dependencies, arise when groups must rely on each other to complete a task (Thompson 1967). From an organizational perspective, the complexity of integrating knowledge increases as the number of dependencies between different groups or specialized domains increases to produce a product or service. Moreover, when the cycle of knowledge integration is repeated and circumstances change, the task moves from integrating existing knowledge between multiple stakeholders to jointly determining what and whose knowledge is now relevant to meet a customer's new requirements. More than being a case of simply transferring knowledge, it becomes a process of creating shared agreements (Nonaka 1994) across interdependent groups. Because dependence generates complexity and the need for mutual adaptation in knowledge integration, *the amount of dependence between sources of knowledge* is also a core knowledge integration challenge. Knowledge transfer frameworks that fail to account for highly iterative task dependency may seriously underestimate the integration challenge faced by groups in organizations.

Finally, dependence implies differences in knowledge, that some individuals are more experienced than others, or that they are specialized in different domains (Smith 1976/1776, Weber 1947/1924). Differences in amount and/or type of knowledge are necessary to meet the production demands for complex products or services. But the unique terminology, tools, practices, or incentives that define each domain also establish knowledge boundaries across domains. In complex product development settings, each specialization often must create new knowledge to meet the more challenging new requirements. The creation of new knowledge can be disruptive to existing relationships between domains of specialization, however, which means that dependencies must be redefined and renegotiated. This might involve, for instance, the time and energy to establish a new shared language, method, or artifacts that facilitate the creation of a collective solution (Carlile 2002). Given the potential impact of these differences on the dependences that define the knowledge required, *the amount and/or type of specialization or difference between sources of knowledge* is another core knowledge integration challenge. Because the amount and type of knowledge required in complex tasks have dual natures, we will use the words "difference" and "specialization" somewhat interchangeably throughout this paper.

Although existing theories do not address the impact of these three characteristics on the task of integrating knowledge, they have difficulty in adequately scaling from the most simple to the most complex cases of knowledge integration. In situations where the underlying context for knowledge integration is stable, shared language and methods will probably develop between groups (i.e., sender and receiver) over repeated interactions that allow for straightforward communications. This is the realm where information processing or transfer frameworks (Lawrence and Lorsch 1967, Galbraith 1973) provide adequate procedural explanations.

But these situations are not representative of the types of challenges that even modest-sized industrial firms and other organizations face in their knowledge integration activities. Many organizations face competitive environments where novelty is high and the nature of the product or service creates many dependencies and differences. These situations are more challenging because increasing novelty creates the need to transform knowledge (Carlile 2002); at the same time, however, increasing amounts of dependence and difference constrain the organization's ability to transform knowledge (Carlile 2003). In circumstances of strong specialization individuals who do not share enough background or common methods may have difficulty setting conflicts that arise across knowledge domains. Organizations or individuals who seek knowledge integration, therefore, face both the challenge of learning about what is new and the challenge of changing their current knowledge to accommodate the creation of solutions across specialized domains.

In what follows, we provide empirical examples to illustrate the impact of novelty, dependence, and specialization on the complexity of the knowledge integration task, and to illustrate the methods used by organizations and individuals to deal with those challenges. By framing the knowledge integration task as a cycle of transforming knowledge we gain a better understanding of how organizations deal with the consequences generated by novelty, dependence, and specialization.

3. Different Studies, Similar Insights

The empirical evidence in this paper comes from two existing studies of the flow of knowledge in technology/product development settings. These studies shared the objective of understanding the detailed steps, tools, and processes that people and organizations use to create new technologies. Study A investigated technology transfer in an international joint venture (JV), and drew on a large sample of observations. It sought to understand how a specific technology is identified in one location and successfully transferred or integrated into use at another. Study B focused on the classic product development challenge of integrating multiple specialized stakeholder inputs into a new product. While they focused on different literatures, both studies drew similar conclusions about the underlying phenomenon of knowledge integration.

The setting of Study A was a JV formed in the early 1990s comprising operating divisions of three large multidivision, multiproduct global chemical companies (Rebentisch 1995). Data were collected over a period of more than three years using multiple sources, including interviews, archival records, and longitudinal surveys. The result was a dataset comprising 128 cases of technology transfers. The interview and archival data are the primary sources for this discussion. Informants were asked to identify technologies that had been transferred to or from another site, to describe the attributes of those technologies and their organizational and technological context, and to discuss any key differences or similarities between their own firms and their partner firms during the transfer process.

Study B involved a nine-month ethnographic study in a small product development firm that supplied environmental fuel systems to domestic and international auto manufacturers (Carlile 1997). Because the purpose of the research was to understand how a person's functional "practice" (Bourdieu 1977, Lave 1988) constrained collaboration, individuals were observed working within the functional areas of sales, design, manufacturing, and production, and also working formally and informally across boundaries (e.g., cross-functional meetings or informal problem solving). These observations revealed not only how knowledge constrained collaboration, but also how various types of boundary objects and processes effectively managed the boundary across domains (Carlile 2002).

4. Empirical Findings About the Cycle of Knowledge Integration

We focus on presenting selected representative findings from both studies to illustrate how novelty, dependence, and specialization affect the transfer and integration of knowledge in organizations.[1] These findings demonstrate that integrating knowledge is a cyclical process that requires adaptation and transformation.

Novelty. In each study, the organizations faced a source of novelty (i.e., new demands, customer requirements) in their operating environments that precipitated the knowledge integration efforts and activities that were studied. In Study A, the JV partners operated in mature markets that were experiencing increased global competition. While their technologies were relatively mature, competitive pressures due to a variety of factors forced each firm to innovate and differentiate itself from its competitors. The JV's motivation was that each partner offered the others a unique and complementary source of potential

[1] It is impossible to elaborate upon all the data and findings from these two studies in the space allotted. We refer interested readers to the studies themselves for more in-depth examination of the data, analysis, and findings.

competitive advantage. For instance, the U.S. partner could potentially benefit from the production efficiency and predictability of the Japanese partner. Key product and process technologies available from the Japanese partner could allow the German partner not only to strengthen its position in existing product markets, but also to expand into new markets it had previously had difficulty entering. The Japanese partner faced the challenge of producing its product in two new arenas—in the newly unified European market, and at another company's facility. It also sought to benefit from some of the U.S. partner's technologies and operating philosophies that enabled very low production costs. While there was a large degree of overlap in the general types of products produced at each site, the specifics—often dictated by idiosyncrasies of national markets and specific customers—meant that the technologies to be transferred were surprisingly novel to each of the partners.

In Study B, the on-board vapor recovery valve (OVRV) represented the largest new business potential for the company in its history. The organization had been designing and manufacturing various fuel system valves and components for over 15 years and consistently produced superior products. The OVRV, however, represented something quite new and different. The U.S. Environmental Protection Agency (EPA) was now requiring automakers to design their gas tanks so vapors would no longer escape through the tank's filler neck. It would be much larger, containing nearly four times the number of parts of any previous valve, and would also house the functionality of two additional valves to save precious fuel tank space.

In both studies, new requirements drove the organizations to draw upon different knowledge domains in new ways. In Study A, market evolution demanded new solutions that spanned national and organizational technical requirements and the levels of experience with a given technology. As the partners later found, these solutions in many cases also spanned system boundaries, challenging existing practice relating to product composition and production system architecture. In Study B, the boundaries were drawn primarily by the depth and types of specialized expertise within the same organization. The OVRV, however, departed significantly from the existing product architecture, so it required functional groups such as design, manufacturing engineering, and production to face new and difficult technical requirements that demanded significant trade-offs.

Dependence. Dependencies across the groups constrained the generation of solutions to these novel circumstances, so no group was entirely free to pursue an agenda that exclusively benefited its own area of specialization. The partner firms in Study A were highly constrained in what they could or could not do to address their new requirements. They continued to serve existing customers, and because each firm supplied merchant markets, not the end user, their product was part of an engineered system. Their product specifications had to meet strict requirements for physical properties as well as chemical composition. The continuous process production equipment required to do this represented a significant capital infrastructure comprising numerous interdependent subsystems; all these subsystems had to work in concert to meet product requirements economically. The transfer of a single technology element from an interdependent system seldom yielded the sought-after benefits. The partners discovered, usually by trial-and-error, the extent of the interdependencies embedded in the system and what grouping or subset of system elements was needed to reproduce a specific capability at a new site. Thus, changes to the composition of the product or the processes used to produce it had to be understood fully from a variety of perspectives to ensure that they did not violate any of the stakeholders' requirements and so generate negative consequences over time.

In Study B, a critical dependency among the key parties presented itself in the challenge of taking a working prototype and producing it at high volume, while keeping the cost and quality within the targeted range. The goal was not just to produce a few working prototypes, but eventually to produce 10,000 OVRV valves per day. However, because the research and development (R&D) prototype had successfully proven itself in a test run with the customer, the design engineer was now less willing to make trade-offs with manufacturing that might compromise the current functionality of the design. Given the newness of the valve's requirements (i.e., its complexity and high volume) the consequences of the dependency were unexpected and had to be resolved.

Specialization. While dependence demands that groups interact and adapt to achieve a common solution, specialization or difference in type of knowledge localize not only knowledge, but also requirements. As the amount of specialization increases, these interdependent differences generate negative consequences. To resolve these negative consequences, groups need to make trade-offs between specializations; this requires that each group understand and be able to represent its knowledge to the other. In Study A, each of the partners could trace back the technological heritage of its products and processes a few decades to a single firm that pioneered the product. Over time, each of the partner firms had pursued different customers and markets, and those choices affected (and effected) the evolution of their product and process technologies. The U.S. partner's largest market was a class of products that emphasized low cost over high technical performance. Consequently, many of its production technologies emphasized high throughput at the lowest possible cost. Another key product feature, its surface quality, was less important in this market segment. The technologies that the U.S. firm used to create the surface quality therefore were tailored to produce a medium-quality, very low-cost finish. The Japanese partner's largest market was a class of products that emphasized high technical performance. Surface quality was paramount in this market, and the customers were willing to pay a relatively high price to receive it. This meant that the Japanese partner used technologies that created a high-quality, more expensive finish. These specific technologies had been used and perfected over many years in the industry.

At the outset of the JV, the Japanese partner was very interested in the low-cost surface preparation technology used by the U.S. partner and initiated the transfer of this technology to one of its facilities in Japan. Initial trials of the new technology in Japan, however, produced a surface quality aberration that would clearly have been unacceptable to the Japanese firm's customers. A protracted experimentation and troubleshooting process at different facilities in both countries identified a number of sources of the problem, including different technical approaches taken by each firm in the selection and production of certain raw materials, and differences in the evaluation criteria used by the customers in each market. In Japan, the customers relied on a number of technical specifications, but visual inspection was also very important. This market specialization proved a significant challenge to what had originally been considered a straightforward transfer of technology from one site to another.

Study B gives more insight into the challenges posed by specialization between functional disciplines. In the company studied, design engineering specialized in designing the product and producing a few prototypes to prove the "functionality" of the design. Manufacturing engineering specialized in creating a high-volume assembly process to produce 10,000 parts per day at tremendously high quality—with an acceptable amount of scrap. This specialized focus on different problems created a situation where design and manufacturing had desired outcomes that were at odds with each other.

One of the biggest conflicts arose when the manufacturing engineer conducted a few assembly tests with some prototype parts of the OVRV without subassemblies and found that the outcomes produced too much scrap because of the quality problems associated with such a large assembly. However, the design engineer resisted moving to subassemblies because it would affect the critical sealing surfaces in the valve and would potentially degrade the proven functionality of the current design. Furthermore, accommodating such changes would also mean delaying by two or three weeks the delivery of the preproduction parts to the customer.

Transforming Knowledge. In neither study could a single stakeholder achieve the gains in performance dictated by new performance requirements; the transformation of knowledge used in a specialized domain was thus often required. Despite the fact that in Study A the task was technology transfer and in Study B it was new product development, both organizations had to develop adaptive and transformative approaches to integrating knowledge. They began by establishing a means of identifying and representing the knowledge that each group or specialization held. Once the knowledge of each group was "on the table" and the relative merits and costs of different solutions could be compared, trade-offs could be made and agreements reached. This pattern highlights two essential knowledge integration capabilities. The first is that, organizations need processes to make explicit areas of dependence and specialization in knowledge. The second is that, with dependence and specialization identified, the organization must identify the appropriate interactions between areas of specialized knowledge that satisfy novel requirements and still meet the constraints imposed by dependent specialized knowledge domains.

In Study A, as the complexities of the technologies being transferred increased, the complexity of communication interactions surrounding the technology transfer also increased (Rebentisch 1997). This shift in complexity of activity was evidenced by a shift from the transfer of handbooks, drawings, and specifications to more varied and iterative forms of interaction including teleconferences, site visits, training, and joint testing of the specific technology implementations. For instance, sufficiently transferring the operating procedures of a new process technology (which included operating procedures, production worker norms and behaviors, and an understanding of the sociotechnical system in which those procedures were developed) involved a combination of several different interaction behaviors that spanned several months and multiple sites. It involved on-site training by peers in a production setting. The number of repeated interactions or cycles provided opportunity for iteration and feedback as relevant specialized knowledge was identified. These activities provided important contextual information to understand the interdependencies associated with that specialized knowledge.

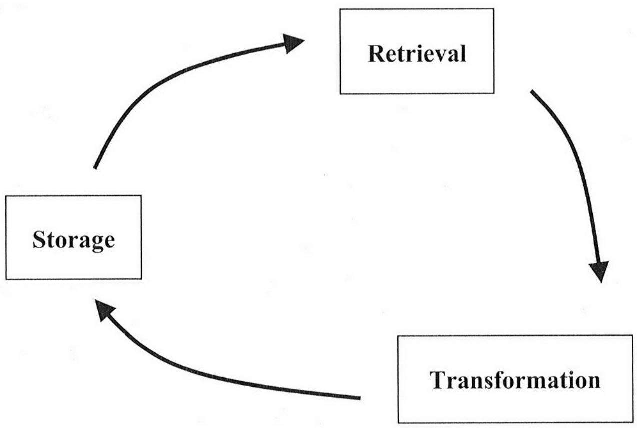
Study B's ethnographic basis provides greater insight into the processes of how critical dependencies across specialized knowledge is collectively identified and transformed. For example, about four weeks before the final design was to be delivered to the customer, the manufacturing and production groups realized the multiple functionality of the valve and its high part count meant that current methods of assembly and testing would not be adequate for the high volume numbers required. However, changing the design would put the proven current functionality of the OVRV at risk and delay the delivery of the final design to the customer. What complicated this even further was that the computer assisted design (CAD) operators did not have time to update the assembly drawings that the manufacturing engineer used to identify the problem with the current design and propose alternatives. Because the assembly drawings did not reflect the current design, the design engineers felt that the changes proposed were not only inaccurate, but that they also could negatively impact current functionality. It was only after an additional CAD operator was brought to develop a set of up-to-date assembly drawings that the manufacturing engineer was able to identify and represent potential downstream problems with the current design, and potential design changes to address those problems. With this shared representation of knowledge, the groups involved were able to refine alternative designs and make critical trade-offs. After a number of iterations (i.e., conversations, follow-up experiments, and meetings between the groups) a new proposal of using subassemblies with a "snap fit" connection was finalized and the design was transformed to accommodate both proper functionality and greater ease of assembly and testing that would reduce scrap rates. Here, transforming the design—transforming the knowledge collectively used—was a process that began with identifying and representing the specialized knowledge of the groups involved, as well as the dependencies that constrained a potential solution. It then involved facilitating a process of sharing, assessing, and transforming knowledge to accommodate a collective solution that addressed the new design's introduced novelty.

These empirical findings have helped describe how integrating knowledge across specialized domains must be seen as fundamentally cyclical to recognize the challenges of adapting and transforming knowledge in complex settings.

5. The Knowledge Transformation Cycle

The knowledge transformation cycle presented here expands beyond existing models to explain the integration of knowledge when novelty, dependence, and

Figure 1 The Knowledge Transformation Cycle



specialization are present (see Figure 1). It has some similarities to the models developed in the organizational learning and memory perspectives (Huber 1991, Walsh and Ungson 1991) and the knowledge transfer model as outlined by Hargadon and Sutton (1997). However, our model has two primary differences from those models. First, our model starts with the storage stage, emphasizing that stored knowledge often serves as a source of path dependency or constrains any retrieval effort. Second, we emphasize transformation over acquisition to highlight the more active effort required to address the path-dependent nature of knowledge when novelty is present. Although the cycle is presented in a linear fashion with distinctive stages, in practice it is not always easy to uniquely define one stage in the absence of others or define where one begins and another ends (Walsh and Ungson 1991). Further complicating this situation is that, as different individuals, groups, or organizations collaborate, they may be at different stages in the cycle in relation to each other.

5.1. Storage: The Accumulation of Knowledge from Past Transformations

Storage, for the purposes of this framework, is defined as the act of adding to the existing knowledge stocks in active use by an individual, group, or organization. In this regard, knowledge storage in an organizational sense is similar to organizational memory (Walsh and Ungson 1991) and the accumulation of knowledge as recognized in learning curves (Argote et al. 1990). Knowledge storage is therefore a process, whether intentional or unintentional, that leads to accumulated knowledge. Stored knowledge may range from written files to digital media, or knowledge embedded in tasks and artifacts to the experience individuals develop in a particular community of practice (Lave and Wenger 1991, Brown and Duguid 1991).

Individuals' and groups' activities and routines are the primary drivers of what knowledge gets stored. Activities without novelty[2] also provide little opportunity to acquire new knowledge, because routine activity does not require new knowledge. Individual or organizational activity that is in part motivated by novel conditions, however, provides opportunities to modify or increase the various stocks of accumulated knowledge.

An example from Study A illustrates how knowledge accumulates in different forms as a result of different paths taken over time. Managers from the U.S. partner quickly noticed that production workers at the Japanese partner sites had a very different approach to the use of operating procedures in production. While the U.S. partner had operating procedures that occupied volumes (and were kept in a cabinet in each of the production control rooms), the Japanese partner's procedures were brief, simple, and to the point. Part of the reason for the approach used by the Japanese partner was the diffusion of the Toyota production system philosophy across Japanese industries with its reliance on the worker's knowledge as an enabler to continuous improvement (Ohno 1988). Employees were recruited from a local workforce with a solid basic education in mathematics and science. They then entered an intensive on-the-job training program that involved rotation through different areas of production, apprenticeship with a "master operator" in each area, and gradual increases in production roles and responsibilities over a period

[2] It is important to note that novelty may be imposed by internal as well as external factors. The concept of continuous improvement in the Toyota Production System is an example of how novelty can be imposed on routine operations by the organization itself. Indeed, many improvement processes in so-called brown field sites may be considered as introducing novelty into a stable or routine state to generate opportunities for change.

of years. This took place in a team environment where new employees were socialized into the norms, values, and operating behaviors of the group, enabling cohesive group action during production. Based on this common foundation, simple operating procedures could adequately store the key elements of production operations and the operating philosophy of the Japanese partner. The simplicity of the explicit operating procedures and their active use meant they were consistently developed and uniformly applied by the Japanese production employees.

The U.S. partner drew its employees from a rural workforce weak in mathematics and science education. These employees were trained on the job, but by means of an ad hoc process that left each employee with a different set of experiences and understanding of the production process. Production experts (i.e., industrial engineers) wrote painstakingly detailed operating procedures to create a uniform set of procedures, but the extensive nature of the procedures meant that employees tended to consult them only in extreme circumstances. In fact, managers from the U.S. partner complained that the production workers' working knowledge was contained in small pocket notebooks—individualized notes on what to do under different conditions that had been generated through years of experience. But because each employee's experience tended to be different, it was difficult for the U.S. partner to establish the stable conditions necessary for systematic improvement activities (i.e., the controlled introduction of novelty through experimentation for the purpose of learning and improvement). The different forms of stored knowledge used at each site illustrate the various processes whereby knowledge accumulates over time, and the different forms in which it is stored. The example also illustrates how knowledge storage is dependent on the specific activities, contexts, and paths pursued.

Whether stored intentionally or unintentionally as a result of individual or organizational activity, stored knowledge serves as a source of competitive advantage if it can be reused in a way that increases effectiveness or otherwise reduces knowledge retrieval, transfer, and transformation costs. When the knowledge integration task has remained stable and novelty is very low, knowledge storage and its reuse can be straightforward. Here, differences and dependencies have largely been specified through past activity (e.g., in the form of databases, formal methods, and reports) so stored knowledge can be readily reused and conneted to other sources of knowledge.

However, even under relatively routine circumstances, knowledge storage in organizations may be a passive, haphazard, or neglected process. "Lessons learned" databases may capture only a fraction of the total working knowledge in use during the previous activity cycle. Moreover, knowledge embedded in practices, processes, or artifacts may be stored in a way that causes it to be "forgotten" or otherwise unavailable during future knowledge retrieval, though it still retains relevancy to future applications and decisions. There are many reasons why organizations fail to store knowledge effectively. For instance, once a product development project is complete its budget and schedule have generally been exhausted and new projects with new customer demands beckon. There is often little time or money to document the processes and key decisions that defined the previous knowledge transformation process. The extensive production system knowledge contained in the operating procedures binders at the U.S. partner site illustrates knowledge that was present and relevant, but unavailable and not a part of the working knowledge of the production operators. Instead, their working knowledge was experientially based and captured in small accessible notebooks.

With increasing novelty more challenging issues emerge. While specialized domains may be able to document the path they took to arrive at a new design, the challenge of representing collectively the dependencies across knowledge domains is a daunting management task. In some cases, future product novelty may render obsolete the knowledge stored from the current cycle, making deliberate storage progressively untenable and, in some cases, establishing barriers to innovation. Experience suggests that for radically new product generations or technologies, reuse of large amounts of stored knowledge is difficult because underlying technologies change, significantly higher product performance requirements require radical modifications, or scope and complexity almost guarantee that even exceptionally low error rates will still produce some failures. Under such circumstances it becomes difficult to justify the benefits of large investments in knowledge storage due to a low potential return from knowledge reuse.

5.2. Retrieval: Searching for and Assessing Relevancy

Knowledge to be retrieved may reside in people, or it may be embedded in processes or artifacts. Knowledge retrieval does not begin from a clean slate; it is based on a path-dependent history of activities within the organization. In many situations, such history is of significant value as individuals retrieve and reuse knowledge and experiences to meet their needs. However, as task complexity increases, the scope of activities associated with the retrieval process needs to adapt to address not only the increase in the application of knowledge, but also the increased number of dependencies and sources of specialized knowledge.

One way to describe the retrieval process is in terms of information search (March and Simon 1958, Cyert and March 1963) and knowledge acquisition (Huber 1991). Retrieval involves identifying knowledge that is likely to result in the satisfaction of a need or solution to a problem. This involves two iterative efforts. The first effort is the search for knowledge sources that may be useful, and the second is the assessment of those knowledge sources and whether they are relevant to the task at hand, and thus worth acquiring. The iterative efforts between search and assessment can be described as two overlapping spaces. The first is the domain of knowledge sources that might eventually provide the solution—the search space. This search space evolves in scope or breadth over time as additional knowledge suggests new avenues of inquiry or the closure of others. Evolving from this search space is a set of possible solutions—the solution space. The solution space may range in size from a single-point solution to a set of alternatives that vary according to different requirements and interests. The process of assessing the relevance of the knowledge generated in the retrieval process in part defines the relation between the two domains. The specialized backgrounds and values of the participants in the retrieval process determine the utility of the knowledge in addressing the task at hand, as well as the credibility of the knowledge source. From this ongoing relationship between search and assessment comes a smaller, more manageable set of knowledge sources than the original search space would have provided.

Knowledge representation moderates the search and assessment processes during the retrieval stage. How a specialized form of knowledge is represented at its source will determine in large part whether it is even identified or considered part of the search space and, ultimately, the solution space. As knowledge becomes more highly specialized, it develops its own terminology, nomenclature, protocols, syntaxes, and associated rules of thumb—which typically reside with specialists. But the creation of specialists by definition restricts the accessibility of the knowledge by a novice (Hinds 1999) or a specialist from another area (Dougherty 1992). Unless those specialists are able to represent the knowledge within their domain in a useful way to outsiders, it will be as if it does not exist for the purpose of improving the current product or service. The way knowledge is represented therefore influences the degree to which those outside a specialized knowledge domain will be able to understand the knowledge and ultimately make an assessment of whether it is relevant to the solution space.

The particular problem that we face in this complex task is that knowledge developed within different practices constrains or shapes action, value, and choice along different pathways. The issue of knowledge representation identifies the connection between storage and retrieval, and the practical questions of addressing the way novel situations will be handled, where dependencies lie (i.e., whom to talk to), and what is valued by one's group (i.e., specialization). Stored knowledge only proves useful to individuals when it is retrieved and then employed to claim something of value to them (Bourdieu and Wacquant 1992). Knowledge retrieval, therefore, is motivated by the demands of a value-creating activity, anchored in the backgrounds and interests of the groups involved.

There are several examples of the importance of representing specialized knowledge and determining its relevance from the empirical studies. In Study A, managers from the U.S. partner were particularly impressed by the production yields of their Japanese partner. To understand what was required in transferring this technology, high-level site visits and production audits were used to provide detailed knowledge about the specific product and process capabilities at the Japanese site. This collaborative experimentation was necessary because the observable aspects of the production system did not adequately represent the full extent of the interdependencies that governed its behavior. The search for the knowledge that underlay the systemic sources of the Japanese partner's high production yields were best represented through complex activities such as site visits, rather than just through more codified representations of their production process.

In Study B, because the company was a small firm, it actually kept all the products that had been designed (including prototype parts) in drawers. This method of storing artifacts that represented past knowledge and approaches proved particularly useful in product design conversations. The tangible objects identified approaches proven in the past as possible solutions to current design problems. Individuals could pick up, point to, and debate the merits of proposed solutions through the aid of past designs. However, given the novelty of the requirements of the OVRV (i.e., high part count and multiple functionality), the knowledge stored in the past products did not represent a subassembly design. The example of the OVRV is useful in highlighting the often problematic links between the storage and retrieval stages. Given the amount of novelty required for the OVRV, past products in physical storage (as well as the experiences and memories of the members of the team) could not or did not easily represent the subassembly design approach. The limited representational capacity of past products not only limited the search space that was available, but also the means of assessing what the proper solution space would be for the design engineers and the manufacturing engineer. What had been done before, the path-dependent nature of knowledge, overly constrained what was possible in the next cycle. Again, seeing these links between storage and retrieval demonstrates the value of framing such a process as a cycle. It also illustrates the critical nature of representing the knowledge, novelty, differences, and dependencies across the groups involved through various people, methods, and artifacts.

5.3. Transformation: Resolving the Consequences and Creating Solutions

The transformation stage begins as relevant knowledge sources have been identified in the solution space. In cases where novelty is very low or where the dependencies between specialized domains remain stable (i.e., well-defined boundaries or interfaces), the simple transfer of knowledge can be a sufficient strategy for sharing knowledge between individuals, groups, or organizations (Argote 1999, Winter and Szulanski 2001). However, as novelty increases, the differences and dependencies between groups often generate negative consequences that must be jointly resolved; the specialized knowledge to be integrated must be transformed to deal with the consequences identified and to generate a collective solution. The challenge of creating new knowledge is not merely to make tacit knowledge explicit between groups (Nonaka and Takeuchi 1995), but also to redefine, negotiate, and transform the knowledge used to accommodate the creation of a collective solution (Carlile 2002). Here again, knowledge representation plays a key role in this stage of the cycle.

The transformation of knowledge is played out in two realms: across specialization and within specialization. The bottleneck to knowledge transformation is typically across specialized domains because domain specialists often lack a common knowledge or syntax for representing and interpreting the knowledge of other domain specialists. Opening up this bottleneck requires, at the least, the establishment of a shared language or, in more complex settings, the establishment of a shared method that allows for negotiation and trade-offs of the ways knowledge from specialized sources will contribute to the outcome. This shared context provides participants a tangible and locally relevant means of specifying their differences and dependencies. Because this process of transformation takes time, the shared method that participants engage in should improve their ability to represent, specify, and negotiate the transformation of their knowledge with each iteration (Carlile 2003).

Key to the development of an effective shared context is the representation of knowledge through the use of boundary objects (Star 1989) and the boundary processes they establish and facilitate (Carlile 2003). An effective boundary object (Carlile 2002) establishes a shared language for representing knowledge, provides a concrete method for learning about differences and dependencies, and facilitates a process for transforming knowledge. Whether these boundary objects are technical specialists (people), mutually accepted methods, or shareable artifacts, they facilitate not only the representation of knowledge but also its potential translation and transformation. The boundary objects used also indicate the degree of inclusiveness of the process in terms of who defines the representation, and who can contribute to or modify it. Without the common means of representing and applying one's knowledge in an across-domain setting, some participants might withdraw from or even hamper the knowledge integration process.

The boundary objects and processes observed in Study A included product samples, process hardware, and production audits and pilot production facility experiments. The most common element, however, was site visits that allowed partners to develop a shared context and language to more easily identify important specialized knowledge and the dependencies that accompanied it. In Study B, the up-to-date assembly drawing provided a means whereby both design and manufacturing engineers could represent their respective knowledge contributions in a way that successfully led to the subassembly redesign of the OVRV.

When the bottleneck of across-boundary knowledge transformation has been addressed, the bottleneck may shift to within specialized domains. The use of predictive models, simulations, and other productivity enhancements to core functional processes allow more rapid retrieval, representation, and sharing of specialized knowledge within a domain. Through the use of these tools, trade-off studies can identify potential positive or negative consequences of the use of specific knowledge. In Study B, the lack of CAD operators delayed the development of an assembly drawing, which hampered the ability of the manufacturing engineer to represent his knowledge to the design engineer. After an additional CAD operator was assigned to help the manufacturing engineer produce the production drawings, the bottleneck in knowledge representation and transformation shifted back to the boundary between the design and manufacturing engineer. Efforts to represent and transform knowledge within a given specialized domain are generally much easier because a common language, shared artifacts, and shared methods are more easily established and maintained. These within-specialization tools provide an important contribution: they prevent the within-specialization contributions from becoming a bottleneck to the more challenging process of transforming knowledge across boundaries.

5.4. And Again: Implications of the Cycle

Because we argue that knowledge is created in practice or activity (Suchman 1987, Schön 1983), the active processes of knowledge transformation determine what knowledge is created and, potentially, stored for later use. Stored knowledge can be retrieved for reuse in a new transformation cycle if it is seen as relevant, and more specifically, if it is represented in a way that facilitates its retrieval. Representation is determined in part by the processes used to store the knowledge when it was created. The mutual influences across stages remind us of the limitations of describing the cycle as a linear process beginning at one point and ending at another. What we have also begun to anticipate in the repetition of the knowledge transformation cycle is the importance of knowledge representation. What knowledge is stored (and how) affects what knowledge is searched and how it is assessed, which affects what knowledge ultimately is transformed. The success or failure in a cycle is not just determined by what is processed or transferred, but also by the capacity to represent knowledge, and the novelty and differences that are of consequence to the interdependent groups.

6. Discussion

The empirical observations from these studies highlight the importance of novelty, dependence, and specialization in explaining the challenges of knowledge management and organizational learning in complex settings. Both studies illustrated how specialized knowledge sources and the dependencies that constrain them were shaped by the knowledge transformation activities from previous cycles. Through the perspective offered by the knowledge transformation cycle, the amount of novelty present from one cycle to the next becomes key to determining the contingencies surrounding the types of activities required for successful knowledge integration.

Novelty is an appropriate basis for such a contingency approach because of its direct impact on two key transformation cycle processes: knowledge storage and knowledge retrieval. Knowledge accumulates or is stored during transformation activities, which defines in large part what knowledge is available for later retrieval. The effectiveness of knowledge storage and retrieval in the absence of active knowledge transformation processes will be driven by the extent to which current demands match past activities. When novelty is very low, knowledge from previous cycles can be reused, so knowledge representation is relatively straightforward. Most existing knowledge dependencies are sustained, so the introduction of any new knowledge takes place within a more known and specifiable context. Formal knowledge storage strategies, such as information technology to capture and store information in databases for later retrieval, may prove sufficient in many cases to the knowledge integration task at hand. However, systems for capturing knowledge must ultimately justify their existence through economies of knowledge reuse—the savings provided from knowledge reuse must more than offset implementation and maintenance costs.

As novelty increases and disrupts past relationships between specialized sources of knowledge, the reuse of stored knowledge grows more problematic. The knowledge contributions needed are more difficult to predict based on prior experience, so the representation of available knowledge becomes increasingly important for successful retrieval. In such situations, firms must devise more complex arrangements for capturing and representing knowledge across cycles. Some firms have developed effective strategies for defining product architecture arrangements (Henderson and Clark 1990) that represent specialized knowledge and dependencies and facilitate knowledge reuse. This shifts the focus to storage strategies that better represent the dependencies and specialized forms of knowledge in active use. Examples include product family architectures that allow mass customization and economies of scale at low model rates (Cusamano and Nobeoka 1998), and other modular architectures (Baldwin and Clark 2000) such as open (or proprietary) standards, common interfaces, or nomenclature that work to stabilize the boundaries across which knowledge must be integrated. These strategies reduce the cost of retrieval and transformation, although they increase cost by requiring activity to define those interfaces (i.e., transforming and storing additional knowledge).

In cases where novelty is higher, boundary objects provide a more active means of specifying the dependencies of consequence across specialized domains. In the two empirical contexts discussed, people, processes, and artifacts not only represented the differences and dependencies between groups but also facilitated a process whereby additional learning and knowledge transformation could take place (Carlile 2003). In new product development settings the value of artifacts and prototyping methods are critical in improving innovation (Carlile 2002, Schrage 1999, Clark and Wheelwright 1995). When conditions are more stable, boundary objects can be reused from cycle to cycle. However, as the amount of novelty increases, the organizational capability necessary for successful knowledge integration shifts from one of efficiently *using* (exploitation) current boundary objects to one of effectively *creating* (exploration) boundary objects that represent sources of difference and dependence that are now of consequence.

For an organization to effectively integrate knowledge in complex settings in the long term, it must build the capacity to manage knowledge storage, retrieval, and transformation over multiple cycles. An example of building a firm-wide capacity can be seen in the infrastructures that Toyota has established to support its "continuous improvement" efforts (Ohno 1988, Spear and Bowen 1999). These infrastructures include employee training, job rotation, localizing problem solving, across-locale problem solving, shared methods, and prototyping. From the perspective of the knowledge transformation cycle presented here, this can be seen not only as a capacity of learning within a given cycle, but also as a distributed organizational capacity to learn across domains.

6.1. Implications for Research

Most approaches to knowledge management in organizations (and by extension, management research on knowledge management) emphasize storage and retrieval processes. The knowledge transformation cycle presented here highlights an overall cycle and mutual influences across the stages of storage, retrieval, and transformation, and how they are affected by the relative amounts of novelty, dependence, and specialization present. This more complete view provides a basis to improve our approach to knowledge management and our understanding of the types of artifacts, activities, or tools employed and their relative capacities and costs as conditions become increasingly novel.

Knowledge representation has emerged as a critical feature in the storage, retrieval, and transformation stages. Given the importance of knowledge representation, some key questions emerge. For instance, what are the underlying mechanisms for knowledge representation in complex social and technical settings? What knowledge elements must be effectively represented in storage and retrieval, and what is the net effect of such representation? Are detailed representations of the specialized knowledge sources employed and their dependencies sufficient, or are the intentions and interests of those who generated this knowledge architecture also necessary to judge the relevance of what is retrieved? How will various tools or activities that have enabled economical knowledge representation in the past be effectively reused and managed in future cycles, given increasing novelty? More research is needed to address the challenges in reusing and creating particular representational artifacts and activities, tools, and technologies.

The development of this knowledge transformation cycle also suggests that many learning models and metaphors are inadequate in describing the complexities of organizational learning. As outlined here, organizational learning is a social process with multiple actors possessing unique knowledge and interests. Given the nature of this collective, yet dependent, structure organizational learning cannot be simply understood as an aggregation of individual learning, or as individual learning anthropomorphized at an organizational level. Cycles are relational in that the nature of learning and knowledge flows across boundaries. Learning is relational in that there are always at least two actors—two individuals, two groups, two organizations—each transforming knowledge within its own domain, yet interdependent at a boundary in a collective knowledge transformation cycle. Based on this description, the conceptual question of appropriate level of analysis gives way to a more practical question of the unit of analysis—that is, the relational properties between two actors, the difference of their respective knowledge, and the effectiveness of such knowledge represented to each other at the boundary.

7. Conclusion

In this paper, we have examined the task of integrating knowledge in complex technology and product development settings. When scrutinized as a cycle, many questions arose concerning the ability of current theory to adequately explain the consequences generated by the path-dependent nature of knowledge. Drawing upon two empirical studies, we proposed and then outlined three stages of a knowledge transformation cycle to augment the limitations in current theory. By specifying the stages of this cycle and the consequences that arise when the cycle is repeated, we were able to identify three primary issues. First, novel requirements imposed a challenge on the reuse of knowledge as defined by its previous use. Second, under such conditions, to accommodate past knowledge and develop new solutions, knowledge must be jointly transformed by those involved. Third, given novel conditions, the mutual influences between how knowledge is stored, retrieved, and transformed outlines not only the practical challenges of representing knowledge, but also begins to identify the broader challenge of developing a capability for learning across specialized domains. These insights also have direct bearing on our understanding of what boundary objects and processes support an organization's learning capability to deal with competency traps (Levitt and March 1988) and sources of rigidity (Leonard-Barton 1995) that arise in competitive environments.

References

Argote, L. 1999. *Organizational Learning: Creating, Retaining and Transferring Knowledge*. Kluwer, Norwell, MA.

——, P. Ingram. 2000. Knowledge transfer: A basis for competitive advantage of firms. *Organ. Behavior Human Decision Processes* **82** 150–169.

——, S. Beckman, D. Epple. 1990. The persistence and transfer of learning in industrial settings. *Management Sci.* **36** 140–154.

Baldwin C., K. Clark. 2000. *Design Rules: The Power of Modularity*. MIT Press, Cambridge, MA.

Bourdieu, P. 1977. *Outline of a Theory of Practice*. Cambridge University Press, Cambridge, U.K.

——, L. Wacquant. 1992. *An Invitation to Reflexive Sociology*. University of Chicago Press, Chicago, IL.

Brown, J. S., P. Duguid. 1991. Organizational learning and communities-of-practice. *Organ. Sci.* **2**(1) 40–57.

Carlile, P. R. 1997. Transforming knowledge in product development: Making knowledge manifest through boundary objects. Unpublished dissertation. University of Michigan, Ann Arbor, MI.

——. 2002. A pragmatic view of knowledge and boundaries: Boundary objects in new product development. *Organ. Sci.* **13**(4) 442–455.

——. 2003. Transfer, translation and transformation: An integrative framework for sharing and assessing knowledge across boundaries. Forthcoming.

Clark, K., S. Wheelwright. 1995 *The Product Development Challenge: Competing through Speed, Quality, and Creativity*. Harvard Business Press, Cambridge, MA.

Cusamano, M., K. Nobeoka. 1998. *Thinking Beyond Lean: How Multi-Project Management is Transforming Product Development at Toyota and Other Companies*. Free Press, New York.

Cyert, R., J. March. 1963. *A Behavioral Theory of the Firm*. Prentice-Hall, Englewood Cliffs, NJ.

Darr, E., L. Argote, D. Epple. 1995. The acquisition, transfer and depreciation of knowledge in service organizations: Productivity in franchises. *Management Sci.* **41** 1750–1762.

Dougherty, D. 1992. Interpretive barriers to successful product innovation in large firms. *Organ. Sci.* **3** 179–202.

Epple, D., L. Argote, R. Devades. 1991. Organizational learning curves: A method for investigating intra-plant transfer of knowledge acquired through learning by doing. *Organ. Sci.* **2**(1) 58–70.

Galbraith, J. 1973. *Designing Complex Organizations*. Addison-Wesley, Reading, MA.

Grant, R. M. 1996. Prospering in dynamically-competitive environments: Organization capability as knowledge integration. *Organ. Sci.* **7** 375–387.

Hargadon, A., R. Sutton. 1997. Technology brokering and innovation in a product development firm. *Admin. Sci. Quart.* **42** 716–749.

Henderson, R., K. Clark. 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Admin. Sci. Quart.* **35** 9–30.

Hinds, P. 1999. The curse of expertise: The effects of expertise and de-biasing methods on predictions of novice performance. *J. Experiment. Psych.* **5** 205–221.

Huber, G. 1991. Organizational learning: The contributing processes and the literature. *Organ. Sci.* **2** 88–115.

Lave, J. 1988. *Cognition in Practice: Mind, Mathematics, and Culture in Everyday Life*. Cambridge University Press, Cambridge, U.K.

——, S. Wenger. 1991. *Situated Learning*. Cambridge University Press, Cambridge, U.K.

Lawrence, P., J. Lorsch. 1967. *Organizations and Environments: Managing Differentiation and Integration*. Harvard Business School Press, Cambridge, MA.

Leonard-Barton, D. 1995. *Well Springs of Knowledge: Building and Sustaining the Sources of Innovation*. Harvard Business School Press, Cambridge, MA.

Levitt, B., J. G. March. 1988. Organizational learning. W. R. Scott, J. Blake, eds. *Annual Review of Sociology*. Annual Reviews, Palo Alto, CA, 319–340.

March, J. 1972. Model bias in social action. *Rev. Ed. Res.* **44** 413–429.

——, H. Simon. 1958. *Organization*. Wiley, New York.

Nelson, R., S. Winter. 1982. *An Evolutionary Theory of Economic Change*. Belknap Press, Cambridge, MA.

Nonaka, I. 1994. A dynamic theory of organizational knowledge creation. *Organ. Sci.* **5**(1) 14–37.

——, I. Takeuchi. 1995. *The Knowledge-Creating Organization*. Oxford University Press, Oxford, U.K.

Ohno, T. 1988. *Toyota Production System: Beyond Large-Scale Production*. Cornell University Press, Ithaca, NY.

Rebentisch, E. 1995. Knowledge in flux: The transfer of technology and practice in an international joint venture. Unpublished dissertation. Massachusetts Institute of Technology, Cambridge, MA.

——. 1997. The link between technology complexity and communication: Complexity in international technology transfer. Working paper, International Center for the Management of Technology, Massachusetts Institute of Technology, Cambridge, MA.

Schön, D. 1983. *The Reflective Practitioner: How Professionals Think in Action*. Basic Books, New York.

Schrage, M. 1999. *Serious Play: How the World's Best Companies Simulate to Innovate*. Harvard Business Press, Cambridge, MA.

Smith, A. 1976/1776. *Wealth of Nations*. Oxford University Press, Oxford, U.K.

Spear, S., K. Bowen. 1999. Decoding the DNA of the Toyota production system. *Harvard Bus. Rev.* (Sept./Oct.) 97–106.

Star, S. L. 1989. The structure of ill-structured solutions: Boundary objects and heterogeneous distributed problem solving. M. Huhns, L. Gasser, eds. *Readings in Distributed Artificial Intelligence*. Morgan Kaufman, Menlo Park, CA.

Suchman, L. 1987. *Plans and Situated Actions*. Cambridge University Press, Cambridge, U.K.

Szulanski, G. 1996. Exploring internal stickiness: Impediments to the transfer of best practice with the firm. *Strategic Management J.* **17** 27–43.

——. 2000. The process of knowledge transfer: A diachronic analysis of stickiness. *Organ. Behavior Human Decision Processes* **82** 9–27.

Thompson, J. 1967. *Organizations in Action*. McGraw-Hill, New York.

Walsh, J., G. Ungson. 1991. Organizational memory. *Acad. Management Rev.* **16** 57–91.

Weber, M. 1947/1924. Trans. A. H. Henderson, T. Parsons, eds. *The Theory of Social and Economic Organizations*. Free Press, Glencoe, IL.

Winter, S., G. Szulanski. 2001. Replication as strategy. *Organ. Sci.* **16** 730–743.

Accepted by Linda Argote, former department editor; received March 4, 2001. This paper was with the authors 9 months for 2 revisions.