Collaborating Across Boundaries: Theoretical, Empirical, and Simulated Explorations

by

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Submitted to the Sloan School of Management
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ABSTRACT

Complex goods and processes require ever more sophisticated and specialized knowledge; harnessing multiple kinds of expertise to execute tasks, solve problems, and develop strategies is increasingly critical to organizations' survival. When specialists come together, however, they often speak in different vocabularies, worry about different problems, use incompatible tools, and occasionally even serve incongruent objectives. Generating value from specialized knowledge requires creating and sustaining collaboration across functional, disciplinary, and organizational lines so that people on each side of a boundary learn what they need to practice their discipline effectively in support of interdependent work. My research examines determinants of success and failure to collaborate across intra-organizational lines.

The dissertation proposes a theoretical framework for examining cross-boundary work and uses qualitative and simulated analyses to explore two cases describing (non)collaboration across boundaries of hierarchy and role. The framework, which emerged through iterative study of field data and literature relevant to cross-boundary work, builds on existing theories of knowledge management, cognition, and innovation and product development and unites them in a way consistent with dynamic theories of structuration and practice. The first case articulates a simple lens integrating three themes in organizational and social theory—daily activities, actors' accumulated resources, and the recursive interactions between these that unfold through time—and turns the lens on a widely cited ethnography describing interactions between doctors and technicians over implementation of a new scanning technology. The second case uses a framework elaborating on each of these themes to explore (non)collaboration across departmental lines in new product development, using data gathered from a midsize manufacturing company.

The contributions center on generating more comprehensive explanations of why (non)collaborative patterns can emerge in cross-boundary work. The research draws on the framework, field observations, and simulation analyses to identify three failure modes of collaboration and to suggest interventions to keep people involved and productive in interdependent work. These include designing locations, artifacts, actions, and timing of cross-boundary activities in light of participants' current knowledge; staffing and training to balance expertise across the boundary; and aligning knowledge gained through cross-boundary work with sanctioned roles and activities in the larger organizational context.

Key words: Collaboration; boundaries; knowledge management; simulation; system dynamics

Committee Chair: Lotte Bailyn
Title: T Wilson (1953) Professor in Management

In memory of Cody, my faithful teacher

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Chapter 1

The Importance of Collaborating Across Boundaries

> A marketing professional charged with bringing a new service offering to market regularly convenes discussions among 40 to 50 people responsible for aspects of the company's operations on the ground, in the air, domestically, and internationally, as well as staff from support functions such as information systems, finance, sales, and human resources. She believes smaller meetings would be more manageable, but she needs these people to talk to each other about ways the new service will alter business assumptions embedded in the company's accounting, information, scheduling, and operational systems and procedures and so affect how they work within and across divisions.
>
> A review of a city's foundering efforts to devise and implement a digital record system calls for heads of the city's planning, operations, and technology offices to "respectfully collaborate" in redesigning work processes that create and use information necessary for day-to-day business in the municipal courts, prison, and child welfare office.
>
> A manufacturing engineer puts off calling a design project manager, to whom he gave the "okay" several weeks ago for a new product under development. The glossy silver paint that will give the product bellwether appeal in the market highlights every snag, every rough spot remaining from fabrication processes. Together they need to decide whether to request immediate investment in new tooling, postpone the project until manufacturing can make the current process deliver suitable results, or go for a distant second-best color of paint.

Each of these scenes points to a need for collaboration across lines of department, region, organization, or role. Increasingly complex goods and processes require more sophisticated and specialized knowledge. Many aspects of competitive advantage are marked by integration of expertise across disciplinary lines, and harnessing multiple kinds of expertise to execute tasks, solve problems, and develop strategies is increasingly critical to organizations' survival and success. In the early 1980s, for example, Federal Express married mundane information about operational logistics with customer desires for delivery confirmation of priority shipments to

create a package-tracking system that established the company as a market leader for more than 15 years (Harvard Business School Case, 1989). Sony's integration of acoustical excellence with engineered miniaturization allowed it to launch wave after wave of new products offering portable sound (Sanderson and Uzumeri, 1997). Long before such goods and services can be hailed as market coups, people whose knowledge differs must talk to each other, explain their work to colleagues who know and value dissimilar ways of working, and figure out how to interweave their incommensurable tools and goals to accomplish together what has not been done, what was believed undoable.

The question is: What do these people do when they are together? What does the city manager do, to whom does she talk, and what does she say to gain agreement on which department owns which data, to help the technology office develop expertise and take a leadership role and yet prevent empire-building? What do specialists from ground operations and customer service say to finance and information technology experts, to make sure that the people on the front lines of the company have the support to execute their jobs when the new service launches? When specialists come together, they often speak in different vocabularies, worry about different problems, use incompatible tools, and occasionally even serve incongruent objectives. Some meetings end with actionable plans and commitments to follow through, while others end with threats of escalation, retaliation, or simply the promise of future non-participation. Generating value from specialized knowledge requires creating and sustaining collaboration across functional, disciplinary, and organizational lines. What enables and sustains collaborative cross-boundary interactions? Could similar resources and means, under other conditions, sabotage collaborative ways of working?

Answering these questions requires understanding the give-and-take of daily work, as well as organizational infrastructures that make possible certain behaviors and prohibit others. Is there a meeting room that even holds 50 people? Is there time and capacity in the press of current operations to produce a prototype and try it out? Is there a budget for travel to headquarters, to the plant, to the green-field site? It requires exploring issues of knowledge representation, communication, and customary lines of power proceeding from hierarchy, managerial favor, and sequential precedence. "I thought you said your people could work out the details." "Oh, that's what you meant by 'needing to do a database load,' that you need *three-months'* lead-time?" "I *did* bring it up before the go/no-go meeting. You heard me, and then you moved to the next agenda item." Understanding why collaborative patterns emerge at some times but not others requires investigating ways that in-the-moment activities can be implicitly encouraged and discouraged by accepted organizational patterns and routines, and ways that emerging interactions can come to challenge and dominate patterns that went before.

I call cross-boundary interactions "collaborative" when participants on both sides of the boundary learn what they need to practice their discipline effectively in support of the work at hand. This often coincides with sustained and collegial conversations and common understandings. Under this definition, however, collaboration does not necessarily require that people "share a vision" for a greater good or seek to resolve conflicts (Gray, 1989; Weisbord, 1992). Rather, they find ways of working in which they mutually learn more about how to use their respective expertise to advance interconnected work. My research examines determinants of success and failure in cross-boundary collaborations. This chapter first describes characteristics of the boundary-crossing work that forms the focus of this study and then

discusses some assumptions underlying the research. The chapter ends with an overview of the dissertation.

1.1 Characteristics of cross-boundary work

The primary attribute characterizing cross-boundary work at the center of this research is interdependence among departments, levels of hierarchy, and roles within an organization. Not all interdependence necessitates collaboration all the time. In stable conditions, for example, work coordinated across departmental lines may be supported by standard operating procedures that embed knowledge of interdependencies and render new knowledge-creating or ongoing problem-solving unnecessary. Change or newness in some aspect of interdependence, however, often occasions need for collaborative interactions. These opportunities can arise from alteration to some element of work that may not be designed or even explicitly recognized by members of the organization. Triggers for cross-boundary collaboration may include deployment of technologies that blur customary divisions of labor; establishing new processes that pass work from one department or region to another; or identifying a new market opportunity or goal. In these cases, the work itself and its emerging needs require that people act in coordination and cooperation. They do not collaborate because they long for more egalitarian ways of working or because they believe, necessarily, that a superior outcome will result if they work together rather than alone. They collaborate because they want to accomplish what is asked of them, and a single domain of knowledge is simply insufficient to do what must be done.

Boundaries crossed in the course of interdependent work are marked by differences in occupational or disciplinary practices. A "practice" may be thought of as internalized

knowledge, or practical know-how (Bourdieu, 1980/1990), to wield the assumptions, methods, and tools customary to a particular kind of work. It includes tacit and explicit knowledge (Nonaka and Takeuchi, 1995) as well as values and assumptions embedded in tools and activities comprising the work. Engineering, for example, values precision in measurements of angles and dimensions, aesthetics of design, and power in performance. Sales values achieving balance among promised volumes and revenues, given estimated costs and margins. Marketing values name recognition, vanguard niche products, and brand equity. Manufacturing values constant pacing, the right tool at the right moment, and physical layouts and scheduling systems that keep unions silent if not happy.

While these values are easily recognized and even taken for granted as inhering in particular groups and roles, they often remain unacknowledged and undiscussed, until confusion at the boundaries brings them to the fore. Language, carrying the weight of embedded practices and individuals' investment in them, becomes problematic as people realize words thought to be understood by all mean different things to different departments. In priority delivery businesses, "location," to marketing staff, means a region of the world where customers receive service; ground operations personnel think of locations as facilities equipped with delivery trucks, airplanes, or automated sorting queues; and information systems developers consider location a four-character code in particular record fields in certain applications and databases, changes to which must be proliferated consistently among the computer systems. Even seemingly simple words can cause confusion: "This new product is going to be big!" Marketing interprets high-revenue; design interprets high-performance; manufacturing interprets high-volume.

Even when work across intra-organizational boundaries is mandated by management, it can be under-organized, in that no one may be in charge of facilitating meetings or creating a

process for working together. Sometimes people involved in collaborative efforts experience confusion about what expertise others are expected to contribute, or who possesses the expertise the project needs. Working across boundaries is also problematic because—as important as integrating disparate kinds of expertise is to competitiveness and viability—much of the business and organizational world thinks and acts in ways that undermine cross-boundary interactions. Indeed, disciplines often reward and promote individuals who know more and more about less and less. Incentives, monetary and otherwise, are usually offered to individuals, not to groups (e.g., Griffin, 1997), and certainly not to ad-hoc gatherings of people working across white spaces of organizational charts and process flows. The business press in both practitioner and scholarly circles remains heavily weighted toward noting and idealizing leadership conceptually and heroes personally (Fletcher, 2002).

In contrast, this research focuses on *processes* of working together, seeking to explain both successes and failures in collaborating across boundaries. I attend to the content of work, different kinds of knowledge that participants bring to the boundary, how participants represent what they know to one another, and who speaks to which issues and when and why. I investigate not a particular moment typifying cross-boundary interactions but patterns of interactions through time and their effects on the work at hand. In keeping with a process view, this research explores relationships among aspects of doing and communicating work and how they sustain or undermine patterns of interaction in which each participant learns what she needs to contribute effectively.

1.2 Research questions and underlying assumptions

The questions shaping this research include:

Why do similar people in comparable settings sometimes evolve collaborative ways of working and other times develop uncollaborative patterns of interaction?

Are there particular settings or tools or timing for cross-boundary interactions that especially enable an organization to achieve desired outcomes of interdependent work?

The research undertaken for this dissertation examines collaboration across boundaries within organizations, lines formed by levels of hierarchy and differences in department or role. Although interdependent work frequently includes representatives from multiple divisions and roles, I focus on two-party interactions to explore a core form of the phenomenon. Assumptions underlying the research include: that parties bring different kinds of resources—in particular I focus on knowledge—to a boundary; that the content and nature of the work affect how they exercise their knowledge at the boundary; that activities at the boundary can in turn affect what people know about their work; and that history of individuals and groups matter through the accumulated resources they bring and through ways of interacting customary to the practices of their disciplines and roles.

Studies of cross-functional interactions reveal challenges in creating shared perspectives among various "thought worlds" (Dougherty, 1992; Carlile, 1997). Bourdieu (1980/1990) refers to resources accumulated from playing a particular role as "capital" affiliated with that role, and distinctions among people's types and amounts of capital convey their relative position in a field of social interaction and influence their ability and inclination to act or "play" in that field. I focus on knowledge, or practical know-how (Bourdieu, 1980/1990; Bourdieu and Wacquant, 1992) as a key form of capital in cross-boundary work. People draw on their accumulated

capital in order to act competently in any given situation. Because capital has value only within the situated practices in which it takes shape—an artist's skill proves useful when she interacts with other artists but not necessarily when she interacts with bankers or a mortgage company, for example—different forms of capital, or different kinds of knowledge, can become problematic. I assume that specialists bringing different resources to a boundary are invested (Taylor, 1995) in their respective practices. That is, as a person gains more expertise in her chosen field, her ability to demonstrate her competence depends more heavily on the assumptions, methods, tools, and values of that field.

While many kinds of knowing are explicit and codified, others are embedded in our physical beings and in the tools we use to exercise what we know in mundane ways. Whether called tacit (Polanyi, 1966), embodied (Nonaka, 1994) or inhering in the activities and settings of practical cognition (Lave, 1988), expertise includes a component of understanding that is demonstrable only in the context of using that knowledge. Therefore exercise of knowledge is difficult to separate from its content. Growing evidence suggests that the content and nature of work influence ways of interacting (Barley and Kunda, 2001; Bechky, 1999; Carlile, 1997). How people perceive their work and the activities of others can thus be informed by theories of cognition (Lave, 1988) and knowledge representation (Star, 1991; Henderson, 1991). I undertake study of cross-boundary collaboration by attending to the content of work and the tools and actions through which it takes shape in order to comprehend ways that people exercise, or are prevented from exercising, their knowledge of the work at hand.

Such a view draws on theories that assert that situated practices prove a valid object of study because they reveal the social order in which those activities have meaning (Garfinkel, 1967; Weick, 1969/1979). A social order takes shape through mundane activities in which

individuals enact the common-sense knowledge necessary to act in "reasonable" ways and do "reasonable" things (Goffman, 1959; Berger and Luckmann, 1966; Garfinkel 1967). Activities and social interactions play an important role in knowledge creation and knowledge management (Nonaka and Takeuchi,1995; Nonaka, 1994; Brown and Duguid, 1991). Research on communities of practice (Brown and Duguid, 1991;Wenger, 1988) highlights volitional, down-to-earth interactions among people who pragmatically share similar objectives and tools to achieve them. Leonard's (1995/1998) research on innovation underscores interplay between repositories of expertise residing in people's heads, organizational routines, and physical technologies and the activities that make use of and inform that knowledge. In the context of cross-functional work, a subset of knowledge management literature focuses on using boundary objects to aid communication among people of differing expertise (e.g., Henderson, 1991; Carlile, 1997, 2000, 2002). Boundary objects, according to Carlile (1997, 2000) are things that concretely represent differences in the parties' understanding and dependencies among elements of their work; furthermore, robust boundary objects are transformable by each party involved. In this study of collaboration, I assume that activities at the boundary—and the objects, applications, and settings used in those activities—influence patterns of interaction and whether people learn what they need to participate effectively in interdependent work.

This research presupposes that people engaging in cross-boundary work come with individual and collective histories that shape the resources they bring and their willingness to transform or preserve customary ways of interacting. In keeping with theories of practice (Bourdieu, 1980/1990) and structuration (Giddens, 1984; Orlikowski, 1992), I assume that actors' accumulated resources and the activities in which they engage can recursively interact and influence patterns of social interaction across a boundary. This assumption is in keeping

with research focused on technology as a stimulus or catalyst for new social interactions, which suggests there is no guarantee that collaborative practices develop or follow a particular implementation of technology. Rather, social and organizational patterns of interaction are shaped by a technology's inherent characteristics (Barrett and Walsham, 1999; Orlikowski 2000); how people practically appropriate it in their day-to-day work (DeSanctis and Poole, 1994; Orlikowski, 1996), and institutionalized values and norms of the organization implementing the technology (Orlikowski and Yates, 1994; Barley, 1988a).

Researchers asserting dynamic relationships, as structuration and practice theorists often do, are susceptible to the same misperceptions of consequences in complex systems found in research on managerial behavior (e.g., Sterman, 1989; Diehl and Sterman, 1995). Therefore I use dynamic modeling and simulation to check the internal consistency (Forrester, 1961; Sterman, 2000) of assertions about how situated activities and accumulated resources affect each other. Building setting-specific models of boundary-crossing work in accordance with theories of structuration, practice, and knowledge representation and knowledge management allows me to integrate existing social and organizational theories as they relate to the dynamics of collaboration and explore the breadth of their explanatory power.

Research on cross-functional teams (e.g., Ancona and Caldwell, 1992) is inherently tied to the phenomenon of cross-boundary work. Some research on cross-functional teams (e.g., Keller, 2001; Lovelace, Shapiro, Weingart, 2001) emphasizes diversity and conflict among team members and points to benefits to theory and practice from acknowledging heterogeneity within groups. Rather than adopting an "input and output" view common to group theory (McGrath, Arrow, Berdahl, 2000) and conceptualizing groups as entities whose performance depends on inputs of resources and tasks or attributes of these, however, I take a less clear-cut view of cross-

boundary work. I do not assume that a "group" or "team" exists as a unitary body. As Huxham and Vangen (2000) point out, people involved in collaborative efforts are sometimes unsure of the identity of other parties or of the interests they represent.

Scholarship on boundary-spanning (e.g., Allen, 1977; Tushman, 1977; Ancona and Caldwell, 1992; Hinds and Kiesler, 1995) explicitly recognizes boundaries within firms and gaps among departmental and divisional and group routines that make communication challenging. Employing an information-processing view (Galbraith, 1967; Thompson, 1973) that presumes information is self-evident, both representable and represented, boundary-spanning scholarship focuses on recognizing the role of people formally or informally responsible for transferring information across boundaries; their distribution in an organization; and the technologies they use in communication. But common instigators for cross-boundary work, such as new technologies, unfamiliar processes, or previously unattempted organizational goals or market endeavors, often make it hard to "know what we know," and tacit knowledge is not necessarily transmittable or transferable (Polanyi, 1966; Nonaka, 1994). Thus I do not assume that problems (Preston, 1991; Suchman, 1995) or information about their possible solutions are self-evident or obvious in the course of cross-boundary work.

Much of the literature on collaboration centers on alliances between firms (e.g., Gulati, Nohria, and Zaheer, 2000; Kale, Singh, and Perlmutter, 2000; Ahuja, 2000). Research in this vein recognizes resources that parties bring to an interaction but focuses on governance structures for access to those resources rather than processes of using them. It often views collaboration as developing volitionally, for the mutual gain of parties, rather than as emerging necessarily from ongoing interdependent work. Similarly, studies of negotiations and conflict resolution (e.g., Cox, 1996; Gray, 1989) focus explicitly on collaboration across organizational

lines. These studies, however, often emphasize processes to generate collaborative outcomes, defined as those for which all stakeholders have influence and commitment to executing. They presume that need for collaboration arises from recognition of interdependence among groups and individuals and emphasizes processes of bargaining, aligning incentives, and communicating and negotiating about each participant's needs and resources in structured ways, often with designated facilitators or mediators. In contrast, I do not assume that such structured processes and resources, or even recognition that these might be desirable, are necessarily part of work crossing intra-organizational lines.

1.3 Overview of the dissertation

This dissertation presents a theoretical framework for examining cross-boundary work. The framework focuses on three elements in social and organizational theory—daily activities, actors' accumulations of resources, and the recursive relationships between these that play out through time—and incorporates aspects of theories of cognition, knowledge management, and product development and innovation. It describes how these elements relate in contexts of collaborating across boundaries. Participants in interdependent work bring distinct accumulations of expertise in keeping with their differentiated roles to joint activities at the boundary. Dimensions of a cross-boundary activity, such as its location and timing, the artifacts used, and the actions people undertake in the shared setting, affect participants' abilities to represent what they understand about the work at hand and to communicate the difference it makes to others' work. When aspects of jointly performed activities are familiar to a participant, the activities are accessible to her: She learns more about the interdependent work and how to

act competently to help achieve the desired organizational outcome. As people shape and participate in activities at the boundary, patterns of interaction can unfold in collaborative ways, through which all increase their understanding of the work at hand, or in uncollaborative ways, in which learning by at least one party is limited.

The framework's merit lies in generating more comprehensive explanations of why (non)collaborative patterns can emerge. It suggests three knowledge "mismatches" that can evolve in uncollaborative patterns of cross-boundary interactions. First, a mismatch can exist between the knowledge of the work that participants accumulate and their expected role in joint activities. Uncollaborative patterns arise when participants on one side of the boundary gain expertise in aspects of joint activities deemed the rightful purview of those across the boundary and so threaten the roles of other participants. Second, there can be mismatches between levels of expertise in participants on either side of the boundary. Uncollaborative patterns can emerge when people on one side of the boundary know much more than others, perhaps usurping control of the cross-boundary activities, cutting off others' participation or rendering the activities unintelligible to them. Third, mismatches between a participant's practice and the locations, artifacts, and actions of a cross-boundary activity can make that activity inaccessible to her. Uncollaborative patterns can unfold when participants eager to participate and knowledgeable in their role engage in activities designed for people with utterly different abilities. Unable to learn from activities at the boundary, they cannot express their understanding in the vocabulary or tools or actions valued by other participants, and perhaps speak in apparent *non sequiturs* or withdraw from active participation.

These mismatches are interrelated through recursive feedback processes between individuals' accumulated know-how and their participation in and learning from activities at the

boundary, and one mode of noncollaboration can lead to and reinforce other modes of noncollaboration. Using setting-specific simulation models to animate the framework as applied to two cases, I explore how feedback can amplify or attenuate mismatches in knowledge to evolve in (un)collaborative patterns of interaction. Together, the framework and dynamic modeling of cross-boundary interchanges help explicate why patterns evolve as they do and suggest points of intervention to establish collaboration and advance desired organizational outcomes.

The rest of the dissertation is organized as follows. Chapter 2 provides the first articulation of the framework in terms of a "lens" integrating three elements of social and organizational theory—activities that enliven daily work, actors' accumulations of capital (such as expertise); and recursive relationships between these that play out through time. Undertaken as a pilot study to assess the explanatory usefulness of the theoretical lens and co-authored with Paul Carlile and Nelson Repenning, the chapter explores Barley's (1986) widely cited ethnography of doctors and technicians using newly deployed computed tomography (CT) scanning. Although he did not focus on collaboration *per se*, Barley's portrayal of "scripts" between technicians and doctors provides rich data for studying what sustains and undermines collaborative and uncollaborative patterns of interaction. Chapter 2 reviews Barley's case study and, using the activities – accumulations – recursion lens, proposes a single, internally consistent theory capable of explaining all the patterns of interaction observed in the field. With initial conditions suggested by Barley's data, the dynamic model generates patterns consistent with his research. By simulating Barley's speculations about the importance of relative expertise, we demonstrate that relative knowledge across the doctor-technician boundary about how to run the new machine and how to interpret scans can help explain *why* the observed patterns of

structuring evolved as they did. We find that congruence between a participant's knowledge and her expected role in the cross-boundary interaction also play a role in the dynamics observed.

As I worked with my own field data on interdepartmental interactions during new product development, I discovered a need to elaborate on dimensions of jointly performed activities to make sense of the (non)collaborative patterns I observed and their impact on organizational outcomes. Building on the lens put forth in Chapter 2, Chapter 3 proposes an extended framework for examining cross-boundary activities and elaborates on each element in the activities – accumulations – recursion lens. In particular, actors can accumulate resources for their *own* work or for the work of *others'* across the boundary. I describe four dimensions of cross-boundary activities—*artifacts* and the *actions* people take with them, *locations,* and the *timing* of activities in the flow of work —and how these may influence recursive dynamics of individuals' *learning* from activities accessible to their customary ways of knowing and doing work and their ability and inclination to *participate* in and influence them. I incorporate in the lens elements of research in cognition, knowledge management and representation, and product development and innovation in ways consistent with dynamic theories of structuration and practice. The extended framework can aid researchers exploring why particular patterns of joint activities emerge as well as practitioners designing cross-boundary activities appropriate to advancing the work for all parties.

Chapter 4 explores a second field study, (non)collaboration across departmental lines in new product development at a midsize manufacturing company. I examine the tools and methods used during cross-functional reviews of project progress and their role in identifying and resolving latent problems in new product work. Who knows what about the product under development depends on whether these reviews take place at the product development center or

the plant, who is invited, which artifacts are used (from PowerPoint slides and sketches to functioning hardware), and what kinds of actions are undertaken with those artifacts. Qualitative analysis, in terms of the expanded framework, of three types of reviews identifies a commonly occurring mismatch between dimensions of early reviews and the tools, applications, and places familiar to manufacturing and assembly participants. The mismatch results in little participation and learning by either party early in the development process. Drawing on field data, I build a small dynamic model to investigate how review accessibility and timing affect project progress by soliciting or suppressing distributed expertise to identify and resolve project problems. Simulation analysis indicates that imbalance in the amounts of knowledge about new product work across the design-manufacturing boundary can persevere through most of the development cycle, leading to uncollaborative interdepartmental patterns that contribute to "late changes," unless steps are taken to stage reviews highly accessible to manufacturing and assembly early in the development process. Chapter 4 ends with a discussion of new possibilities for representations that make early new product work accessible to non-design review participants, contingent on their kinds and levels of expertise.

Chapter 5 synthesizes findings from the two cases and proposes implications for the research and practice of cross-boundary collaboration. Theorizing about cross-boundary work benefits from attention to participants' differing accumulations of knowledge as well as the artifacts, actions, locations, and timing of joint activities. Identifying these elements in a given setting can point to mismatches between participants' skills and activities at the boundary, which may affect people's ability and inclination to learn from their interactions. I discuss feedback patterns interlocking the physical flow of work and social patterns in cross-boundary work and the increased explanatory power that results from considering together these aspects of work. I

also propose that relative accumulations of expertise to engage in cross-boundary activities provides a view of timing that complements calendar-based and project-flow views of interdependent work. Chapter 5 concludes with consideration of the limitations of the current work and opportunities for future research.

Thus the theoretical framework and the system dynamics modeling method provide complementary views of cross-boundary work. Modeling and simulation can help explore the range of interactions possible under various conditions in a given setting and can suggest timing for cross-boundary activities more likely to yield desired work patterns and outcomes. The framework offers ways of thinking about the artifacts, actions, and locations of cross-boundary activities—given the state of the work at a particular time—more likely to engage participants fully and increase each one's understanding of and contribution to the work at hand.

Chapter 2

Doctor-Technician Interactions over New Technology

Coauthored with

Paul R. Carlile and Nelson P. Repenning

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2.1 Introduction

Difficult social problems are rarely solved using a single expertise. Whether the challenge is developing a new product or reforming a local school, improving organizational performance, however defined, often requires that people with vastly different backgrounds work together to create solutions unimaginable within any single domain of expertise. Successful collaboration not only positively influences productivity and morale, but it is also critical to reaping the full benefit of organizational investments made in the face of increasing complexity and specialization (Teece, 1997). Authors writing for both practitioners and scholars suggest that the key to ongoing viability is to create and use knowledge *across* the organization (Nonaka and Takeuchi, 1995), and the greatest opportunities for improved performance often lie at the interfaces between functional and hierarchical boundaries (Leonard, 1995/1998; Carlile, 2000). Organizations have always looked to technology to catalyze collaboration, and recent advances in computing power and data transmission speed have only heightened this long-standing interest. From dispersed consultants communicating via Lotus Notes to design and

manufacturing engineers using CAD/CAM, many technologies are accompanied by claims that their use will increase collaboration. Empirical research, however, amply documents that increased collaboration does not always follow the deployment of a new technology (e.g. Barley, 1986, 1988a; Orlikowski, 1992; DeSanctis and Poole, 1994; Barrett and Walsham, 1999). In many cases, introducing identical technologies in similar organizations produces vastly different degrees of collaboration.

The wide range of outcomes produced by similar technologies has been the source of considerable energy and activity in the scholarly community. From Barley's study of scanning technology to Orlikowski's analysis of Lotus Notes, detailed, ethnographic studies of technology implementation have produced some of the most innovative and influential theorizing in organization studies. A principal contribution of this line of inquiry is to highlight that the introduction of a new technology occasions a set of interactions far more complicated than was once appreciated. In particular, users' practical appropriation of a technology, which is strongly influenced by an organization's values and institutional characteristics, affects whether the "technology-in-use" becomes collaborative or not (Orlikowski, 2000, states this most clearly, but similar arguments appear in Orlikowski, 1992 and 1996, and DeSanctis and Poole, 1994). Thus, in contrast to earlier views such as the technological imperative, these studies suggest that the characteristics of a specific technology do not fully determine its ability to produce collaboration. Instead, echoing Giddens (1984), these theorists assert that implementing a new technology is a highly dynamic process created by recursive interactions among the technology, human agency, and institutional norms and values.

While powerfully descriptive, existing work has limitations. Most significantly, researchers drawing on structuration theory are often reluctant to specify *which* characteristics of

an organizational context are most important in determining the degree of collaboration resulting from a specific technology and to suggest *how* those important features interact with the technology to create the observed outcomes. As a consequence, few general lessons or propositions have emerged from this line of inquiry, and the existing literature provides little in the way of formal theory to explain the observed successes and failures. While the utility of formal quantitative theorizing is often questioned, the lack of general statements arising from existing empirical work limit both the growth of a body of testable theory and the ability of those with an intervention orientation to improve organizational practices.

With this in mind, this study offers one method for moving beyond the existing, rich descriptions of single episodes towards more formal theories of technology-induced cross-boundary collaboration. While we affirm structurationist arguments that agency plays a significant role in any pattern emerging around a technology, thus imposing important limits on the explanatory power of any theory, we suggest that it is still possible to move beyond abstract labels like "complex," "dynamic," and "recursive." To do so, we propose a theoretical lens for viewing occasions of structuring created by new technology that is characterized by three elements: a focus on the activities that enact organizations, attention to accumulations of capital or "transformative capability" generated by those activities, and the use of simulation to explicitly capture the recursive relationships between them (e.g. structuration).

The main contribution of this study is to provide a method for concretely characterizing the specific causal processes occasioned by the introduction of a new technology. We argue that such specificity has practical value. For theorists, we show that it is possible to speak specifically enough about the relations among the activities and the traditional roles and larger institutional values that influence them to provide a grounded understanding of "structural"

relations that are most consequential (Glaser and Strauss, 1967). For practitioners, our analysis yields a set of concrete suggestions to managers who use technology to improve cross-boundary interactions in their organizations.

As suggested above, several ethnographies have documented situations in which the same technology, implemented in similar organizational settings, induces widely differing modes of interaction across hierarchical or functional boundaries. To demonstrate our approach, we turn to one widely cited effort, Barley's "Technology as an Occasion for Structuring: Evidence from Observations of CT Scanners and the Social Order of Radiology Departments" (*Administrative Science Quarterly, 31,* 1986). Barley documented in detail the interactions between doctors and technicians at two hospitals implementing a new scanning technology (computed tomography, or CT). We find in this work, which describes phases of both uncollaborative and collaborative interactions at each hospital, sufficient data to study the challenges of cross-boundary collaboration. Turning our lens to Barley's data, we use the construction and analysis of a simulation model to induce an internally consistent explanation for why the two units Barley observed evolved as they did. From this analysis we extract some hypotheses that, taken together, provide the next step towards a formal theory of technology-induced cross-boundary collaboration.

To that end, the remainder of the chapter is organized as follows. In the next section we briefly review Barley's data and then provide an overview of our method. In the section that follows, we present our model and the main results of our analysis. In the final sections we discuss the implications of our results for both future work on technology-induced collaboration and, more generally, any theory that attempts to capture recursive dynamics.

2.2 A case documenting a cross-boundary process

Barley's 1986 ethnography documented two hospitals' implementation of CT scanning. During nine months of observation, he noted and characterized the interactions between doctors and technicians with "scripts," recurrent interactions that reveal participants' roles. By analyzing the scripts, he estimated the proportion of operational decisions made by doctors and plotted "centralized decision-making" over the duration of his observation; he concluded that the patterns at the two hospitals differed significantly (see Figure 2.1, reproduced from the 1986 article).

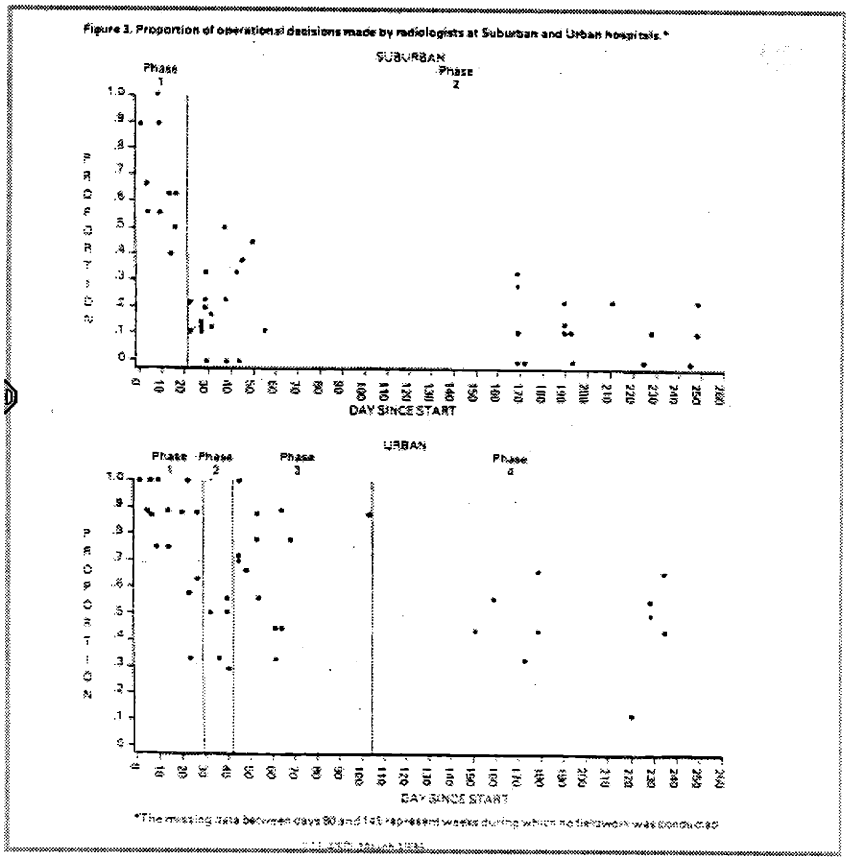


Figure 2.1: Proportion of operational decisions made by doctors at two hospitals

Barley did not focus on whether doctors and technicians in the CT scanning unit worked collaboratively *per se*. But his careful documentation of conversations and modes of interaction between doctors and technicians, categorized into phases marked by changes in staffing arrangements, provides an opportunity to consider the collaborative and uncollaborative nature of those interactions. In fact, Barley's data offer ample evidence that at each hospital during some phases doctors and technicians worked together to produce scans to aid diagnosis and in other phases refused to converse or interact. In Table 2.1, we summarize the phases and scripts Barley documented at the hospitals that he called Suburban and Urban. Additionally, we offer our own characterization of each phase as collaborative or uncollaborative between doctors and technicians, indicated in the rows called "Organizational Pattern."

Suburban			
	Phase 1	**Phase 2**	
Staffing change		Inexperienced radiologists added on day 21	
Experienced with CT	1 of 1 radiologists 2 of 4 technicians	1 of 6 radiologists 4 technicians	
Scripts	Unsought validation Anticipatory questions Preference stating	Clandestine teaching Role reversal Blaming the technologist	
Organizational Pattern	**Collaborative division of labor**	**Uncollaborative division of labor**	
Urban			
	Phase 1	**Phases 2 and 3**	**Phase 4**
Staffing change		Radiologists stay in office to encourage technicians to "figure it out"	Inexperienced radiologists added in day 105, and least competent technicians transferred out on day 105
Experienced with CT	2 of 2 radiologists 0 of 8 technicians		2 of 6 radiologists 4 of 4 technicians
Scripts	Direction giving Countermand Usurping the controls Direction seeking	Unexpected criticism Accusatory questions	Technical consultation Mutual execution
Organizational Pattern	**Uncollaborative nondivision of labor**	**Uncollaborative nondivision of labor**	**Collaborative division of labor**

Table 2.1: Summary of Barley's observations at two hospitals and characteristic organizational patterns for each phase

During Phase 1 at Suburban and Phase 3 at Urban doctors remained near the CT machine and conversed with technicians about the scan taking place. Technicians were responsible for running the machine, and doctors bore responsibility for diagnosis, but they discussed how to conduct the scans in order to aid interpretation of pathology in ways that validated technicians' growing expertise while preserving the doctor's dominant status as the one providing the diagnosis (Barley, 1986: 89-91). As Barley highlights, the degree of collaboration evolved over time, so as doctors become more comfortable with the technician's ability, they accorded them more latitude in making technical decisions. This evolution culminated with "preference stating"; doctors would simply tell technicians what they wanted and offer few suggestions as to how it might be accomplished. We label this interaction pattern "collaborative division of labor."

On the other hand, during Phase 1 and 2 at Urban, doctors often took over running the CT machine because they believed technicians were incompetent (Barley, 1986: 96-98). We label this as an "uncollaborative non-division of labor," since doctors both produced the scans and interpreted them. Another "uncollaborative" mode evolved in the final phase at Suburban, when doctors withdrew from the scanning room to avoid interactions with technicians that revealed the radiologists' ignorance of the features of CT scanning (Barley, 1986: 92-94). As doctors remained in their office with the door closed, they relied on technicians to produce the scans, thus yielding an "uncollaborative division of labor" bearing few hallmarks of working together.

Using Barley's data, we focus our analysis on two central questions. First, given that two similar hospitals implemented identical technology, how did widely different patterns of interaction arise? Second, how did the same staffing change (rotating inexperienced radiologists

into the CT area) produce dramatically different changes in the centralization trends and organizational patterns at each hospital?

2.3 A theoretical lens for studying cross-boundary processes

To study the cross-boundary interactions documented by Barley's research, we draw on existing strains of social theory focusing on organizations. From three theoretical themes—activities (Weick, 1969/1979), accumulations (Bourdieu, 1980/1990), and recursive interactions (Giddens, 1984)—we create a lens with which to view cross-boundary collaboration. We use this lens to examine the activities of those interacting with the technology, the types of capital they consequently accumulate, and how that capital affects subsequent interactions. In this section we discuss activities, accumulations, and recursive interaction as they relate to hospitals' introducing CT scanning. In the following section, we use the simple grammar of system dynamics (Forrester, 1961; Sterman, 2000) as a method for understanding how activities and accumulations interact to generate the patterns identified in Barley's ethnography.

Activities

Weick (1979), Orlikowski (2000) and others (Bourdieu, 1977; Giddens, 1984) have called attention to the daily activities or practices that enliven organizing patterns. The focus on activities is an important reminder of the agency of individuals and the "enacted" nature of their environment. An emphasis on activities underscores the ways in which individuals either conserve or transform existing values, norms, and types of capital. In the interactions between doctors and technicians, we focus on the activities that take place in the CT scanning room,

where technicians are stationed and where doctors can come and go. Doctors' and technicians' use of the CT machine to produce scans is a new activity which, if executed properly, provides the opportunity to improve the diagnosis of patient pathologies. Attention to this activity highlights both the conversations and actions that lead to successful collaboration and the conversations and actions that doctors or technicians undertake to minimize their interaction.

Accumulations

Activities prove important not only because they provide the continual enactment of an organization's daily work and potential points of interaction for people, but also because their influence often endures long after the activities themselves have ended. To portray long-lasting effects of activities, we suggest that activities generate accumulations of capital or transformative capability (Bourdieu, 1980/1990, Bourdieu and Wacquant, 1992). For example, a technician's certification has legitimacy because it is a recognized indicator of accumulations of expertise from a past activity. Perceived accumulations of knowledge lead people to defer to the one present who seems most knowledgeable, most experienced with a given circumstance, or relatively more competent (Bourdieu, 1980/1990).

An individual seeks to use and accumulate capital in keeping with the role she plays in a given social setting (Bourdieu, 1980/1990). We rely on Barley's characterization of scripts to reveal doctors' and technicians' positions relative to each other and the roles they believe they are and should be playing. We posit that two kinds of capital, operational knowledge (ability to use a CT machine) and diagnostic knowledge (ability to render a diagnosis), can be accumulated from the activities that take place in the scanning area. Understanding the accumulations of both

types of capital in both groups is crucial to identifying the potential for cross-boundary collaboration at each of the phases observed at each hospital.

Recursive dynamics

As stated clearly in theories of structuration (Giddens, 1984; Bourdieu, 1980/1990, Bourdieu and Wacquant, 1992), momentary activities and enduring accumulations of capital interact with each other through time. Activities create additional capital, and relative accumulations of capital determine who gets to participate in what activity. Often these interactions conserve the organizational patterns and qualities of living that have occurred in the past. Sometimes, however, people draw differentially on experience to transform and create different organizational patterns. It is at this juncture that most current theorizing ends. Giddens (1984), Barley (1986), Weick (1990), and Orlikowski (1992) have all clearly documented the complexity of the relationship between activities and accumulated resources. But they have often concluded with descriptive characterizations of settings, leaving unspecified *which* activities influence *which* norms and values and vice-versa.

Looking at cross-boundary processes

The accumulations–activities–recursion lens accounts for both enduring norms and values that shape individual activities and ephemeral actions whose consequences can endure long after the actions have ended and the people who produced them have left the scene. Figure 2.2 shows generally how accumulations of capital (shown as a box, or stock, to indicate that the amount of capital can rise and fall and endure through time) and activities interact through time.

The change in capital influenced by activities is shown as a flow, or pipe with a valve, to suggest that the change occurs in the moment and may be large or small.

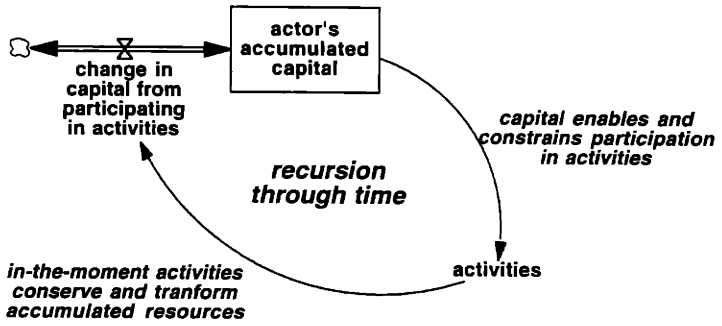


Figure 2.2: Recursive interactions between in-the-moment activities and accumulations of capital

An actor's accumulated capabilities inform in which activities she invests herself and in what ways. As she undertakes certain activities, she conserves or transforms her capital—knowledge, for example, or status or beliefs or tangible outcomes—that in turn enable and constrain her participation in future activities.

When we use this lens to examine cross-boundary activities, it reveals that people on either side of a boundary are invested in different capabilities and accumulate different kinds of capital (Bourdieu and Wacquant, 1992). The activities that draw our attention in this study, then, are cross-boundary aetivities, those performed jointly by people playing different organizational roles and possessing different accumulations of know-how distinctive to their roles. Figure 2.3 portrays the notion that cross-boundary activities are affected by and in turn affect different actors' distinctive accumulations of capital.

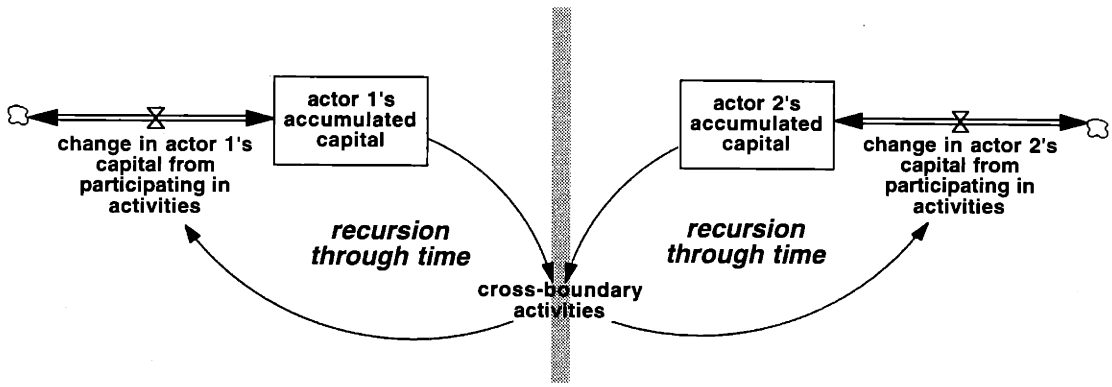


Figure 2.3: Actors' distinctive accumulations of capital recursively affecting and affected by cross-boundary activities

Taking the next step to develop a formal theory requires more concrete specification of interaction patterns that arise in a given setting. We find it useful to articulate explicit relationships between activities undertaken in the CT area, accumulations of operational and diagnostic capabilities, and the social order of radiologists and scanning technicians that comprises the context for this case. We tie these elements together by arguing that activities generate accumulations of capital that in turn affect how the activities take shape, and so affect future accumulations of capital. In keeping with the grammar of system dynamics, we assert that one activity influences another usually through the accumulation of some kind of capital and that an accumulation of capital affects another through some activity (Forrester, 1961). The process of constructing and analyzing a simulation model, capturing the CT room activities, accumulations of knowledge, and the interactions between them, allows us to induce an internally consistent explanation of the inconsistent (i.e., collaborative and uncollaborative) outcomes Barley observed. To make the use of this method more concrete, we turn to analyze the case at hand.

2.4 Using the lens to analyze the case

In Barley's data we identify three specific organizational patterns: collaborative division of labor; uncollaborative *non*-division of labor; and uncollaborative division of labor. In what follows, we address each organizational pattern in turn. We begin with "collaborative division of labor" (as seen in Suburban's first phase and Urban's last phase—see Table 2.1) and present a simple model capturing a network of activities and accumulations that, when simulated, produces the collaborative pattern. Building this model allows us to make explicit the activities, accumulations, and interactions we believe critical to creating the pattern. Then we extend this model to explore the organizational pattern of "uncollaborative non-division of labor" (characterizing Urban's first three phases), in which doctors participate in scanning and actually operate the machine themselves. Next we simulate the changes in staffing rotation that yield abrupt switches in the organizational pattern in both hospitals. Finally, we extend the model a second time, so that it can reproduce the pattern "uncollaborative division of labor" (portrayed in Suburban's final phase) as well as the two organizational patterns discussed previously. In this way, we induce a single theory, comprising a constellation of activities and accumulations of capital and the interrelationships among them, that parsimoniously explains the emergence of each of the patterns observed by Barley, as well as how one pattern transitioned to another. (Documentation of the full model is attached as an appendix to this chapter.)

Collaborative division of labor

We first consider the pattern "collaborative division of labor," observed in the first phase of Suburban and the last phase of Urban. In this pattern, radiologists give technicians some discretion in making decisions, which allows technicians to improve their understanding of the

technology to greater diagnostic advantage. When collaboration is growing, doctors remain in the scanning room, but make fewer operational decisions as technicians learn to operate the CT machine. As highlighted by Barley's data, technicians learn most effectively when doctors participate in scanning and permit technicians to operate the machine as much as their knowledge permits. To explain this pattern in doctor-technician interaction, we focus on technicians' accumulated knowledge of the CT scanner; the activity of doctors' participating in scanning by remaining in the CT room and conversing with technicians while one of them operates the CT machine; and the resulting proportion of operational decisions made by doctors as technicians accumulate understanding.

We represent the technicians' current understanding of how to operate the CT scanning machine as an accumulation, or a stock variable, portrayed by a box (to suggest that the level inside the box can rise or fall through time).

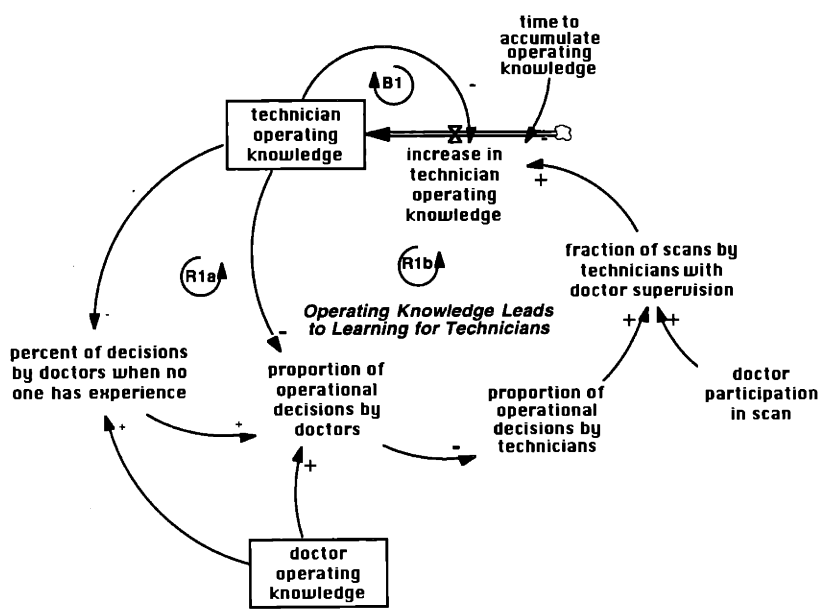


Figure 2.4: Activities and accumulations influencing the level of technician operating knowledge

For the initial example only, we discuss the mathematical representation of the resources, rules, and relationships that Figure 2.4 portrays (complete documentation of the model is available from the authors). In this model, the accumulated resource of technicians' CT know-how is increased by an inflow, *increase in technician operating knowledge*. The equation for this flow is:

Increase in Technician Operating Knowledge =
(Fraction of Scans by Technicians with Doctor Supervision - Technician Operating Knowledge) / Time to Accumulate Operating Knowledge

Here is the rationale for this equation. First, following Barley's description of the CT-experienced radiologist and the CT-inexperienced technicians in Suburban's first phase (1986: 89), we believe that technicians learn when they try new procedures on the machine with supervision of or interaction with doctors. This is congruent with the scripts in which the doctor either asks technicians to perform a procedure and provides feedback on its execution or constructively evaluates the technicians' own decisions (1986: 90). Thus the first element in the equation is the critical cross-boundary activity represented by *Fraction of Scans by Technicians with Doctor Supervision*. Since one cannot learn what one already knows, the amount that a technician can learn at any moment is equal to the current fraction of procedures she is allowed to perform minus her current knowledge level. In other words, how fast she learns depends on the "stretch" between what she is attempting to do and what she already knows how to do—a notion widely accepted in literature on individual learning by doing. Finally, it takes time to accumulate knowledge. To make explicit that technicians cannot learn everything at once, we divide the "stretch" by the *Time to Accumulate Knowledge*. This small model, consisting of one stock, one inflow, and a couple of parameters, creates a balancing feedback loop (labeled B1) that brings the level of technician knowledge towards its potential over time. In system

dynamics, feedback loops provide a way to talk explicitly about recursive dynamics. What a technician has learned already *feeds back* to affect her present rate of her learning. The loop B1 captures the delay inherent in accumulating new knowledge through an activity.

The "rule" we use to represent the proportion of operational decisions made by doctors is shown pictorially in Figure 2.5, in which we portray that doctors and technicians may know only a portion (perhaps overlapping) of all that can be known about operating the CT machine. Adopting a convention common in probability, we assume that knowledge is represented on a 0 to 1 scale and that a specific value represents the percentage of procedures a technician or doctor is competent in executing. We also assume that there is no correlation between the procedures a technician knows and those a doctor knows (in other words, we assume that they are independently distributed). With these assumptions, we then treat the allocation of operational decisions as a straightforward probability problem. We assume that doctors allow technicians to perform all the procedures for which technicians are competent (the entire area of the technician competency circle in the Venn diagram). So we assume that doctors perform only those procedures for which they are competent and technicians are not (this is the area of the doctors' competency circle less the intersection with the technicians' competency). This portion is represented by the *Doctor Operating Knowledge * (1 – Technician Operating Knowledge)* term.

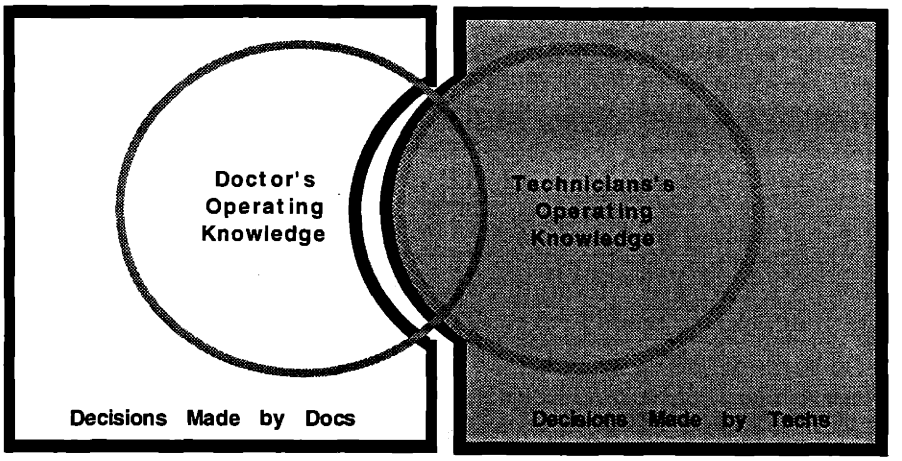


Figure 2.5: Venn diagram showing percent of operational decision-making based on relative knowledge

For those operational decisions for which neither has experience (the area outside of the two circles and captured by the term *(1 - Doctor Operating Knowledge)*(1 - Technician Operating Knowledge)*), we assume that doctors, given their hierarchical position in hospitals, choose whether to make them or delegate them to technicians. We assume that doctors choose based on the relative knowledge of the two groups. *Percentage of Decisions by Doctors When No One Has Experience* is an nonlinear increasing function of the ratio of doctor operating knowledge to the sum of knowledge accumulated by both doctors and technicians. In other words, if inexperienced technicians still seem to know more than doctors about running the machine, doctors will ask technicians to make a greater percentage of the operational decisions for which neither group has experience. Likewise, as doctors appear to have more operating knowledge than technicians, they are likely to assume responsibility for a disproportionately larger share of the operational decisions for which no one has experience. This leads us to the following formulations.

The key parameter in the learning flow is the *Fraction of Scans by Technicians with Doctor Supervision.*

Fraction of Scans by Technicians with Doctor Supervision =
Proportion of Operational Decisions by Technicians * Doctor Participation in Scan

This specifies that the *Fraction of Scans by Technicians with Doctor Supervision* includes only those for which the doctor is in the control room or communicating with the technician about the details of the scanning procedure.

Proportion of Operational Decisions by Technicians =
1- Proportion of Operational Decisions by Doctors

This equation indicates that technicians make decisions about operating the CT machine only when doctors haven't made the decision themselves already.

Proportion of Operational Decisions by Doctors =
Doctor Operating Knowledge *(1-Technician Operating Knowledge) +
(1-Technician Operating Knowledge) * (1-Doctor Operating Knowledge) * Percent Of Decisions By Doctors When No One Has Experience

The formulation for the *Proportion of Operational Decisions by Doctors* captures the dependency between doctors and technicians. Technicians rely on doctors to acknowledge their abilities by allowing them to run the CT machine, and doctors assess the technicians' competence in conducting scans as well as their own. The assumption that doctors choose when to operate the CT machine themselves and when to allow technicians to perform scans reflects our assertion that doctors' authority over technicians results from long-standing accumulated capital attendant to the training, professional practices, and role of "doctor," not only at the field sites Barley studied but in larger society as well. These mathematical relationships are consistent with the notion that as technicians learn more—as they accumulate more capital in the form of knowledge about how to produce CT images—doctors accord them the ability to claim still more capital by learning more. The reinforcing loops R1a and R1b portray the constellation of accumulations and activities and interrelationships central to understanding the "collaborative division of labor" organizational pattern. In Figure 2.6 we have simulated this piece of structure

using the initial conditions for Suburban and Urban based on Barley's data on the nature and level of experience of doctors and technicians staffing the CT unit at each hospital.

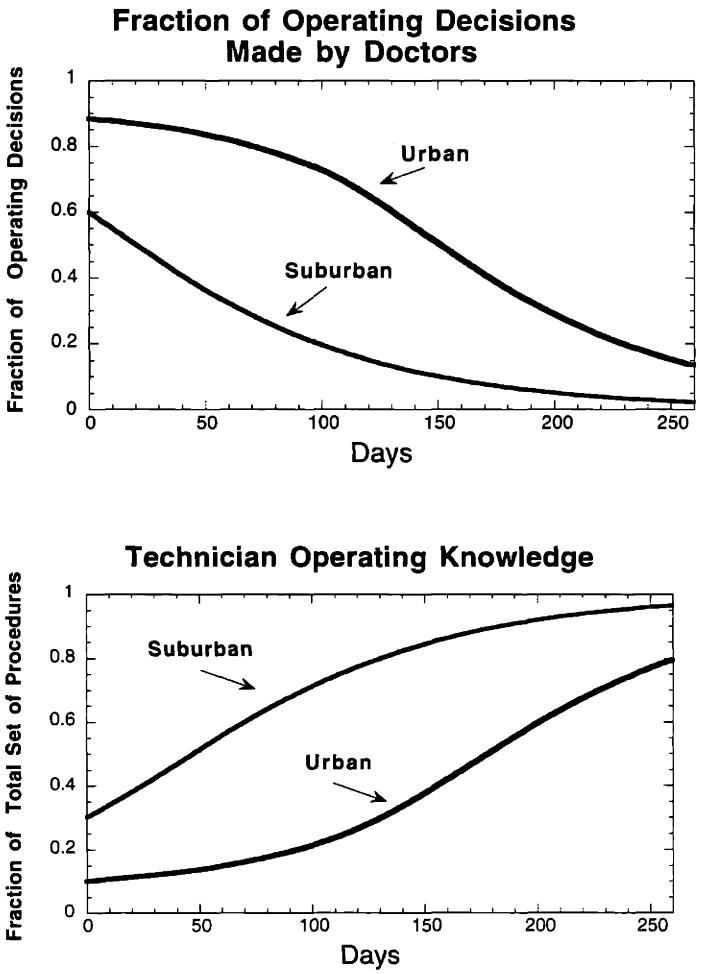


Figure 2.6: Output of small model using
initial operating experience at Suburban and Urban as initial conditions

The simulations, which we run for 260 days to correspond with Barley's period of observation, demonstrate some of the features of cross-boundary interaction revealed by the theoretical lens. First, we focus on the doctor-technician activity in the CT scanning room, necessitated by the nature of the new technology, in which scanning and interpretation are not as separable as in previous technology (Barley, 1986, 1988; Weick, 1990). At each moment, how

many decisions technicians make depends on how much doctors think they know. This leads to our second point: How much technicians know is portrayed by the accumulation of technicians' operational knowledge relative to doctors', consonant with Bourdieu's (1980/1990) concept of capital. The accumulation of technician knowledge grows as technicians each moment build on the knowledge acquired through all their CT activities before that moment. Third, recursive interaction amplifies initial differences in the relative accumulation of operational CT knowledge. As the relative accumulation of CT knowledge influences activities in the scanning room, modest initial differences in expertise produce differences in the amount of procedures technicians are permitted to try, eventually yielding significant differences in the organizational pattern. The positive (or deviation-amplifying) feedback loop reinforces initial differences by affecting the rate at which technicians can learn. In this way, the current relative level of capital constrains and enables access to the activities that generate additional capital.

Uncollaborative non-division of labor

The second pattern, which we label "uncollaborative non-division of labor," dominates the first three phases at Urban. Here doctors make the majority of operating decisions and offer little justification for them. Barley observes first a "negotiated dependence" of technicians on doctors followed by "constructed ineptitude," in which technicians come to rely on doctors' provision of step-by-step instructions. Thus, technicians accumulate little competence in scanning protocols. To extend the model to account for the possibility that doctors usurp the CT machine's controls, as Barley's data indicate, we no longer assume that doctors have a fixed amount of operational knowledge. (In the previous section of the model, we assumed that doctors' operating knowledge remained at the initial experience with which doctors entered the

hospital.) As Figure 2.7 shows, we now represent doctors' operating knowledge as a stock that is increased by their rate of learning.

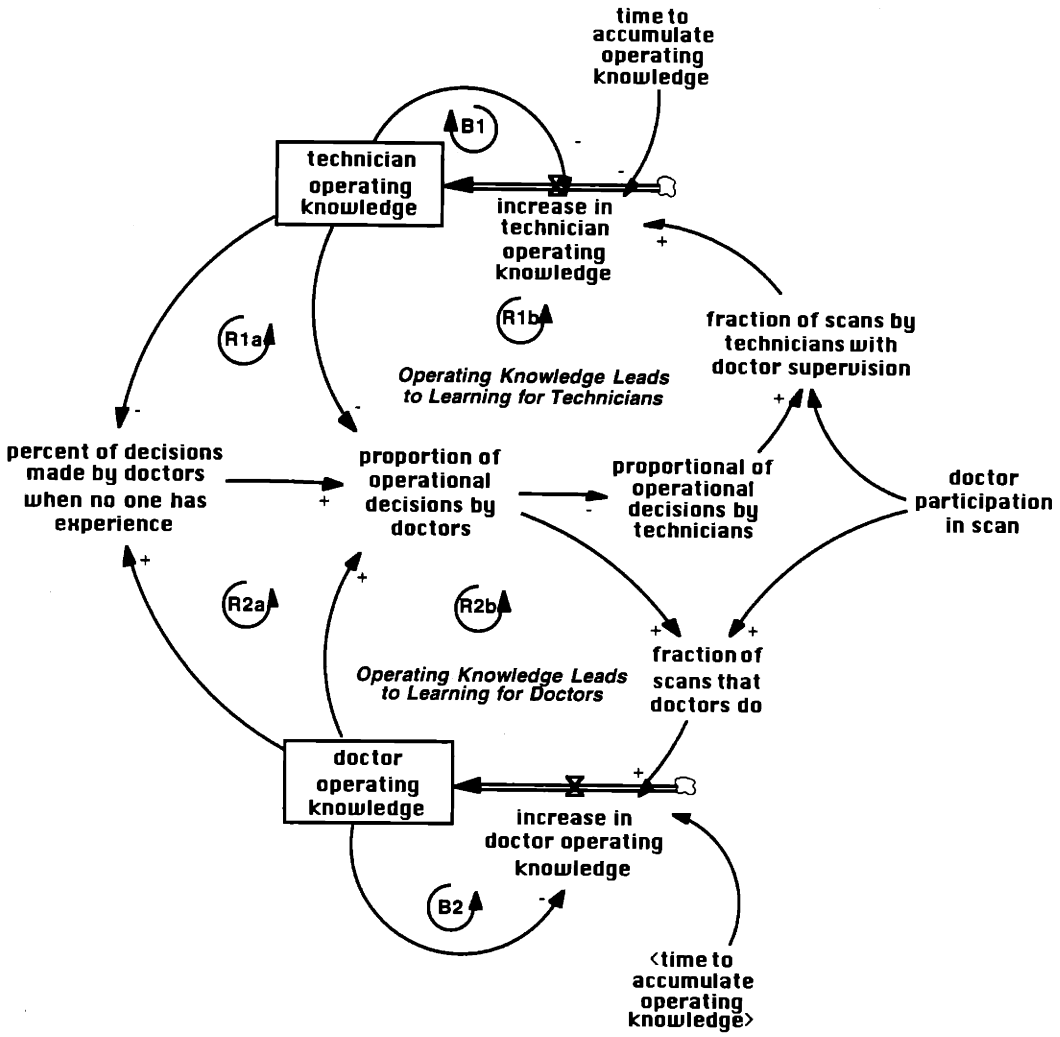


Figure 2.7: Activities and accumulations influencing technicians' and doctors' operating knowledge

We formulate doctors' learning process in the same manner as that of the technicians: Performing procedures beyond those they already know how to do increases (with a delay) the doctors' stock of operating knowledge. As doctors' operating knowledge increases relative to technicians', they are more likely to take control of the machine in tasks for which they feel the

technicians are not competent. So as doctors grow in their ability to operate the CT machine, their inclination to take control of the machine also grows, and, as doctors usurp more control, their competence improves further. These relationships create the positive loops R2a and R2b that can drive the doctors to higher levels of operational competence. The diagram suggests that the causal structures of doctors' and technicians' learning processes are identical, but there is one important difference. We assume that doctors make decisions only over that portion of the procedures for which technicians are not competent. Thus, while doctors may have a high level of operational knowledge, they may perform few procedures if technicians are also competent.

The impact of the additional structure on the dynamics is shown in figures 2.8 and 2.9.

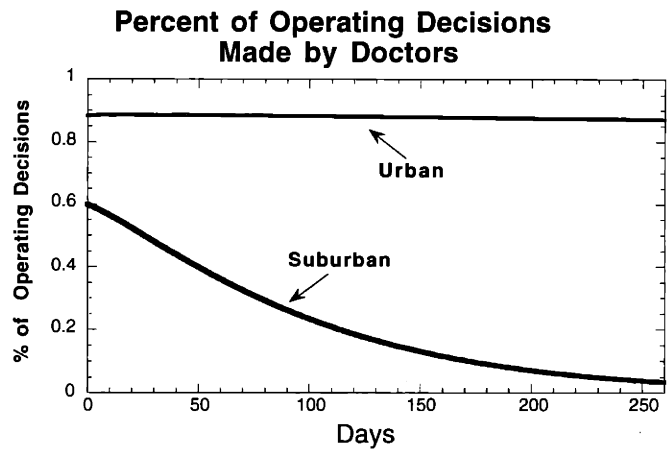


Figure 2.8: Percentage of operational decisions made by doctors in extended model

While the added structure portrays new feedback loops, the results for Suburban are qualitatively similar to that of the smaller model. Technicians start at a relatively low level of operating knowledge but are given some leeway by doctors to attempt new procedures, and so they accumulate knowledge. As technicians' operating knowledge rises, doctors delegate an increasing fraction of the operational decisions. Doctors also accumulate a modest amount of

operating knowledge, but their learning rate slows as they delegate more decisions to technicians, who bear most of the scanning responsibilities by the end of the simulated 260 days.

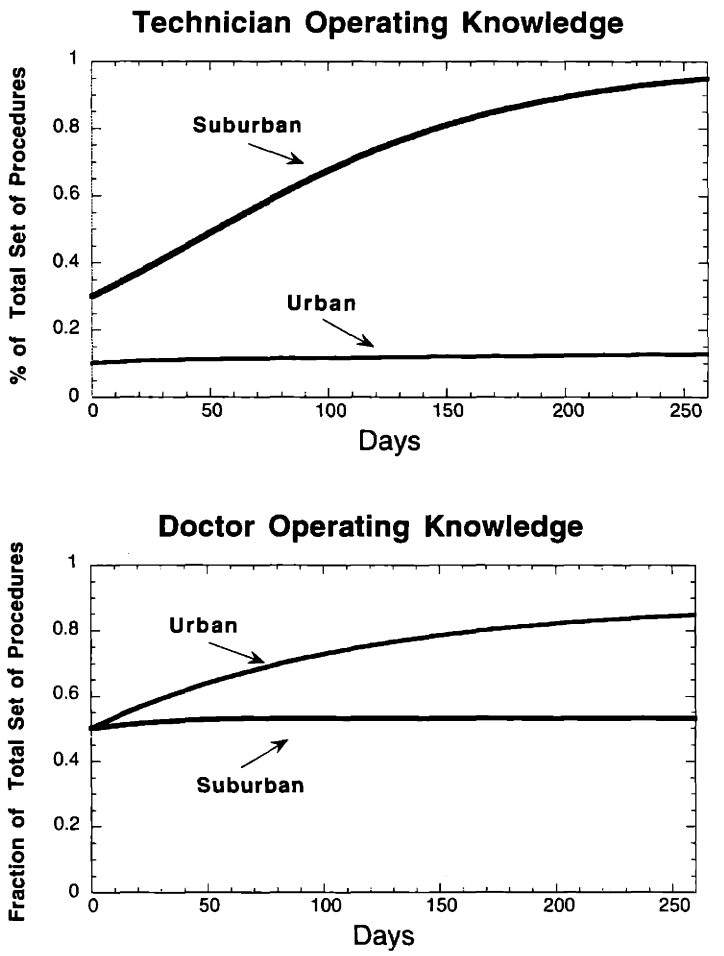


Figure 2.9: Operating knowledge in extended model

The situation at Urban is quite different. As Barley's data suggest, Urban starts with approximately the same level of experience among the doctors but with less experienced technicians, so doctors know *relatively* more. Thus, as Figure 2.9 depicts, doctors initially make a high proportion of the decisions and consequently learn more rapidly than technicians. The fast growth in doctors' knowledge combined with the slow accumulation of technicians' causes doctors to make an increasing proportion of operational decisions. If doctors believe that

technicians cannot produce the images and they themselves can, then they are more likely to take control of the CT machine. Later, as the technicians slowly accumulate operating experience, doctors give them marginally more discretion over the scanning process. This change, however, is minor when compared to the evolution at Suburban.

Whereas in the initial formulation, only technicians could accumulate knowledge, in this extended formulation doctors can also learn. When the pace of doctors' learning exceeds that of the technicians' (because doctors' take responsibility for the actual operation of the machine) the difference is reinforced by the feedback relationships. Doctors learn more, leading them to take more operational responsibility, which results in their additional learning at the expense of technicians.

This set of simulations yields two main points. First, the structure of this small model is identical in both Urban and Suburban, but, as the associated simulations demonstrate, the same structure can produce qualitatively different patterns. Here the different patterns of cross-boundary activity arise from different starting points for technicians' knowledge of the CT machine. This argues our second point: Attending to relative accumulations of expertise is critical to understanding the outcomes of cross-boundary activities. The key difference between the two settings lies in the initial relative accumulations of operational knowledge between doctors and technicians. At Suburban, which starts on a highly collaborative pattern, one experienced radiologist works with four technicians, two of whom are moderately experienced (having transferred from another facility's body-scanning unit). In contrast, Urban "...mobilized to meet the problem [of introducing the new technology] by relying solely on knowledgeable radiologists" (Barley, 1986: 94). These differences in initial relative accumulations, coupled

with feedback processes inherent in learning by doing and the power doctors have relative to technicians, produce significant differences in the patterns of interaction.

Switching from one pattern to another

After deploying CT with experienced radiologists, both hospitals eventually changed their staffing plans by rotating inexperienced radiologists through the CT area and returning the CT-experienced doctors to normal duties in all of the scanning units. Remarkably, the staffing change drastically alters the organizational pattern at each hospital—in different directions. At Suburban, the staffing change takes place at the beginning of the fourth week, and interactions between doctors and technicians shift from a collaborative division of labor to an uncollaborative mode, in which ultimately doctors withdraw from the scanning area. Urban's change in staffing occurs after about 15 weeks and shifts from an uncollaborative mode, in which doctors perform the scans as well as interpret them, to collaborative interactions in which doctors and technicians mutually consult one another. Focusing our lens on Urban reveals how its staffing change alters the relative accumulation of capital, thereby changing the activities at the doctor-technician boundary and creating a new pattern of interaction between them.

During the sixteenth week Urban's four technicians judged as least competent transfer out of the CT group,-and inexperienced radiologists begin rotating through the CT area as the experienced radiologists resume normal duty rotation. Thus a dramatic shift in the relative accumulations of operating knowledge between the two groups takes place. The average level of technicians' knowledge increases, since the more competent technicians are retained, and the average level of radiologist experience drops significantly. We simulate this change in the extended model discussed in the previous section by introducing (at day 105) a 50 percent

increase in the stock of technicians' operating experience and an 80 percent decrease in the average level of doctors' knowledge. The results appear in figures 2.10 and 2.11.

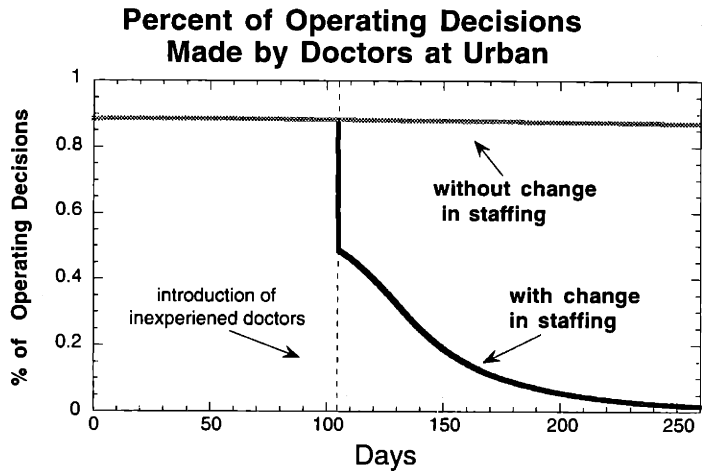


Figure 2.10: Proportion of operating decisions
by doctors with the staffing change at Urban (using the extended model)

After the change, the proportion of operational decisions made by doctors falls (Figure 2.10). This follows directly from the change in the relative amounts of operating knowledge. Most radiologists now have little or no direct CT experience and so rely on technicians. Furthermore, because doctors' knowledge has dropped so significantly, and because technicians learned so little in the previous phases when experienced doctors took control of the CT machine, the collective operating knowledge of both doctors and technicians is quite low. Neither group has much experience—hence significant opportunities for joint learning suddenly become possible.

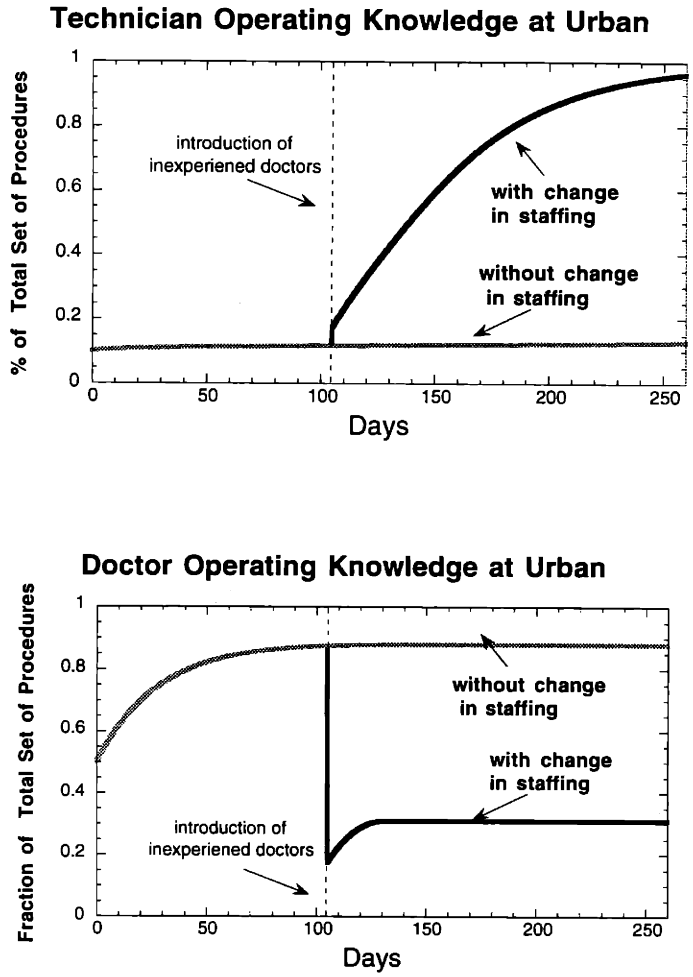


Figure 2.11: Evolution of operating knowledge
at Urban with the staffing change (using the extended model)

In contrast to Urban's pattern before day 105, now technicians do much of the learning. Following the intervention, their competence grows rapidly (Figure 2.11). Doctors, however, learn relatively little, as they now make few operating decisions.

The simulations show that an external change, such as a new staff rotation, can shift an organizational system from one pattern to another. In the case of Urban, by rebalancing the levels of operating knowledge, the staffing change alters the relative strength of the feedback processes, allowing technicians to accumulate more operating knowledge. As Barley writes, the

new rotation system "redistribut[ed] the relative balance of practical experience in favor of the remaining technologists," and the resulting new patterns of interaction "inverted the interaction order established during Urban's earlier structuring...[as] radiologists now became seekers and technologists givers of directions" (1986: 99).

Barley's description of the script "mutual execution" in this phase emphasizes that doctors seek technical information from technicians—that is, doctors ask for instruction in what they consider the technicians' rightful realm of expertise, running the CT machine to produce useful images. In fact, as the technicians' operational competence grows, doctors can claim more of the capital that matters to them, the ability to make accurate diagnoses via CT images. In a complementary way, as doctors reveal their ignorance of technical issues, technicians grow in both their ability and inclination to operate the CT machine competently. The notion that a collaborative organizational pattern depends not only on the relative balance of knowledge between two groups but also on whether the balance is congruent with the expected social order becomes critical as we turn to the third organizational pattern, uncollaborative division of labor.

Uncollaborative division of labor

The pattern of "uncollaborative division of labor" occurs when, in Suburban's extended second phase, doctors withdraw from the scanning control room to reduce the opportunity for uncomfortable role reversals. Barley explains,

> Under radiology's traditional system, radiologists taught technologists, but the reverse was uncommon and nearly taboo. Only the radiologist's front of self-assurance and the technologist's deference, both of which were encoded in the semantics and pragmatics of the exchange, kept clandestine teaching from becoming open instances of role reversal. Yet, open role reversals did occur with some frequency after the fourth week of the scanner's operation (1986: 92).

Role reversals occur when inexperienced radiologists explicitly ask technicians whether the images revealed pathology (rather than about the machine's operation), thus creating discomfort for both groups. To reduce opportunities for awkward exchanges, the inexperienced radiologists "began to withdraw from the scanner's minute-by-minute operation to save face," retreating to their offices, leaving the technicians with considerable autonomy in operating the scanner (1986: 94). The doctors saw the scans only once they were complete.

To capture how the staffing change at Suburban creates these dynamics we extend the model once more. Barley's analysis suggests that the uncollaborative behavior following the staffing change at Urban has its roots in the *diagnostic* knowledge of the technicians. Due to the collaborative nature of the first phase at Suburban, prior to the staffing change, technicians accumulate both skill with operating the CT equipment and some ability to recognize pathology. While openly correcting an inexperienced doctor's off-the-mark question "would have been to risk affront and boldly invert the institutionalized status system" (Barley 1986: 92), the staffing change often required technicians to supply corrective information, albeit in a deferential or tangential way. Such "clandestine teaching threatened the institutionalized roles of radiologists and technologists," (Barley 1986: 92). When doctors perceive their diagnostic abilities as inadequate, their primary form of capital—the ability to make an accurate diagnosis—is threatened. To capture these dynamics, we introduce into the model another kind of capital, diagnostic knowledge, and represent each group's accumulation of it as affected by the learning that takes place while performing scans with doctors present (see Figure 2.12).

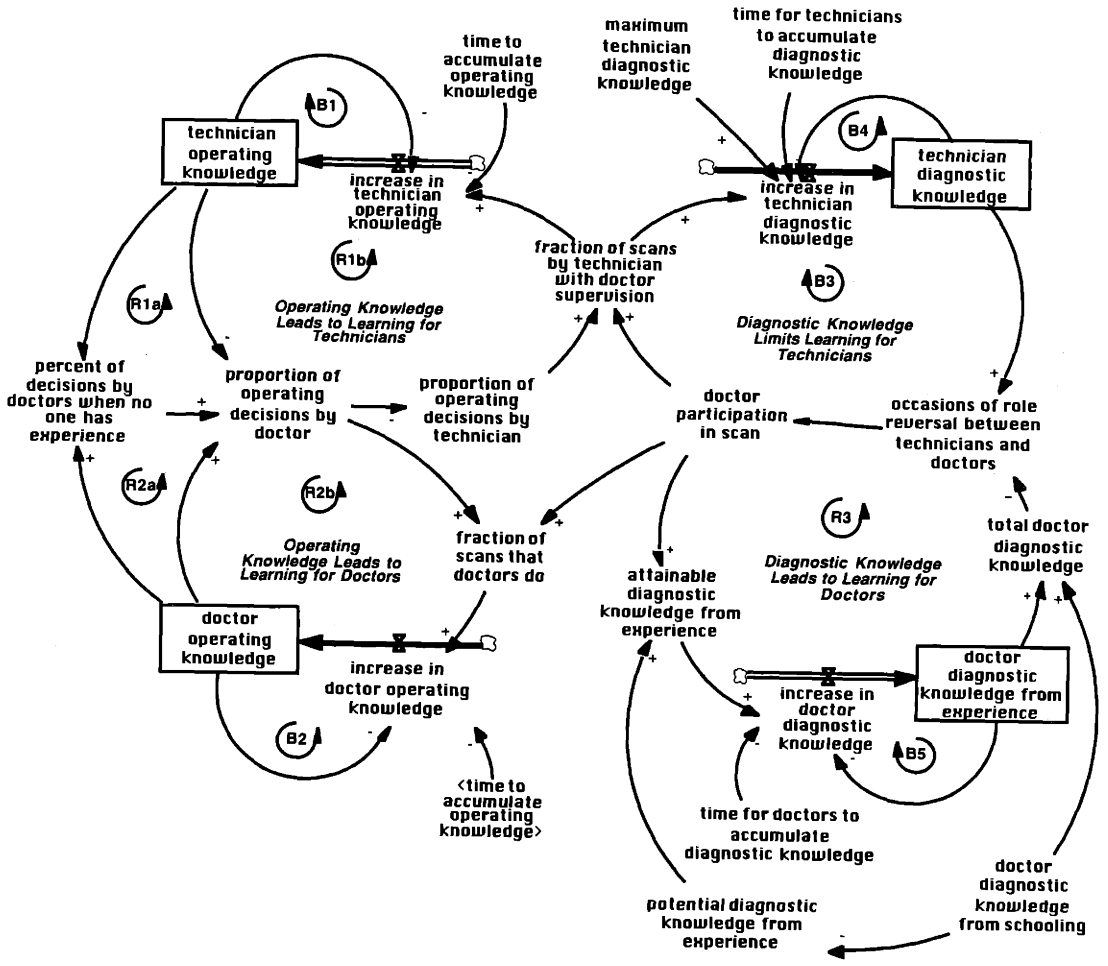


Figure 2.12: Activities and accumulations influencing technician and doctor operational and diagnostic knowledge

Similar to the formulations used for operational knowledge, we assume that doctors and technicians accumulate diagnostic knowledge through learning-by-doing. The inflow of diagnostic knowledge for technicians is increased by the fraction of scans they execute with doctor participation. (This stock of knowledge represents only those skills that pertain to diagnosing the output of the CT scanner, not the full suite of skills associated with being a practicing radiologist.) We assume that there is an upper bound on the diagnostic knowledge that technicians can acquire through experience, since it is unlikely that any amount of on-the-

job experience can provide the understanding of anatomy and pathology gained during medical school and residency. Similarly, we assume that doctors' diagnostic knowledge increases with participation in the scanning process. We assume that doctors enter the CT area with a substantial amount of diagnostic knowledge accumulated either through medical training or work with other imaging technology, such as X-ray. So we represent the doctors' total diagnostic knowledge as the sum of that gained through medical training and that gained from participation in CT scanning.

In this extension of the model, doctors' participation in scanning (previously represented as fixed at 100 percent) becomes a decreasing function of the number of role reversals that occur. The number of role reversals is based on *Technician Diagnostic Knowledge*(1-Doctor Diagnostic Knowledge*), which represents the amount of diagnostic knowledge that technicians have that doctors do not. Following Barley's assertion that role reversals pose a significant challenge to the normal social order, we assume that the function relating role reversals to doctors' participation as quite steep and negatively sloped. Just a few role reversals result in a significant decline in doctors' participation.

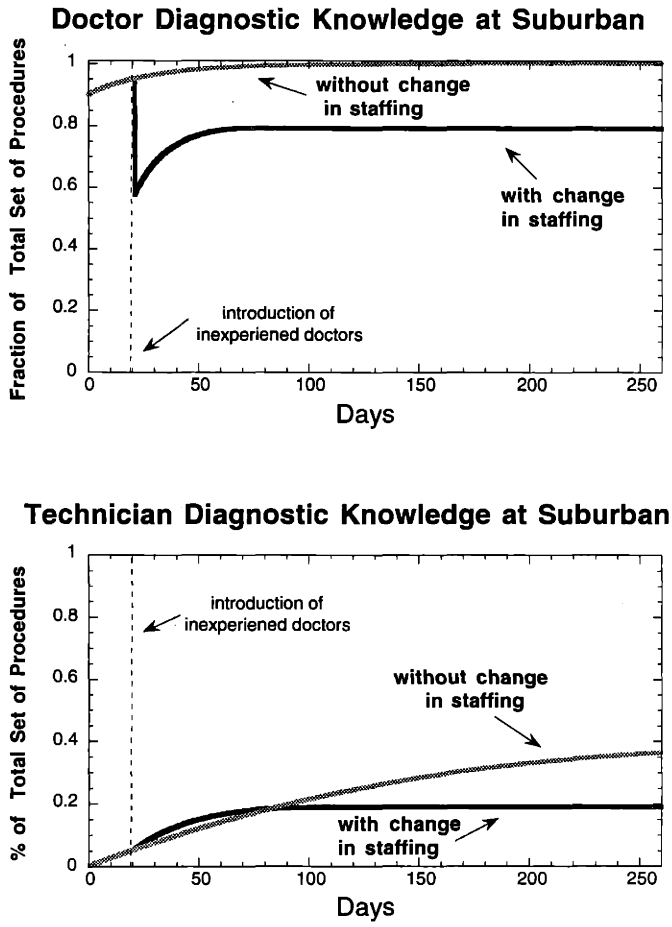


Figure 2.13: Diagnostic knowledge at Suburban (using the full model)

Figures 2.13 and 2.14 show the average level of doctors' diagnostic knowledge falling after Suburban's staffing change on day 21. During the previous three weeks' collaboration technicians accumulated some diagnostic knowledge (approximately a quarter of the projected upper bound), so, when the inexperienced radiologists enter the area, occasions of role reversal increase. Doctors react by reducing the time spent in the scanning area and spending more time "hiding" in the office.

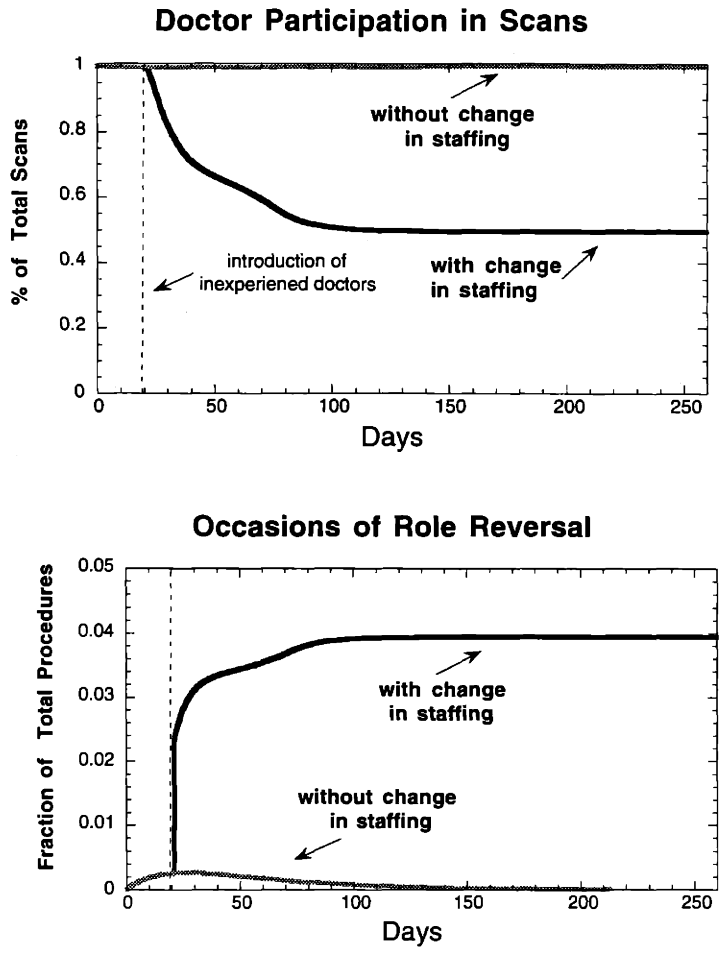
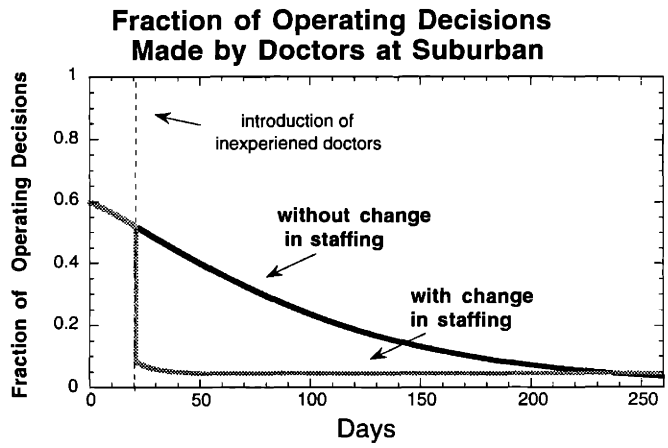


Figure 2.14: Doctor participation and role reversals at Suburban (using the full model)

The doctors' retreat affects the accumulation of technicians' knowledge (Figure 2.15). Initially technicians' accumulation of knowledge grows as they exert more authority in the scanning process during the doctors' absence. These gains are short-lived, however, as their learning is soon retarded by doctors' lack of participation. Thus, in the model, when radiologists withdraw, technicians' total accumulation of operational knowledge falls far short of its potential.



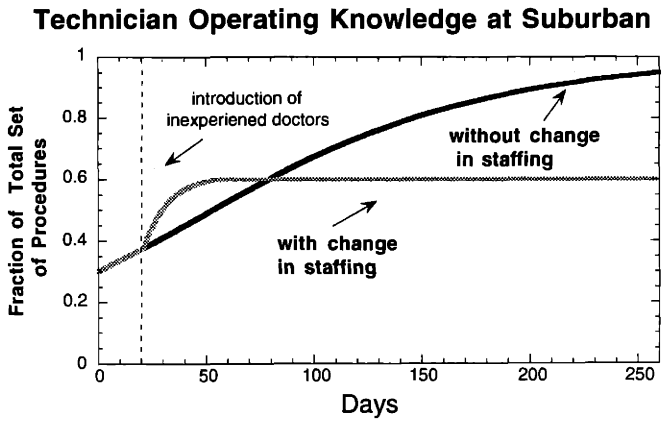


Figure 2.15: Proportion of operational decisions made by doctors and technician operating knowledge at Suburban (using the full model)

To understand the dynamics at Suburban, it is helpful to compare it with a simulation of Urban using the full model. Figure 2.16 shows the accumulations of diagnostic knowledge when the Urban scenario is simulated. As in the case of Suburban, the staffing change causes a significant drop in the doctors' accumulation of diagnostic knowledge. In contrast, however, at Urban doctors' learning does not plateau. Instead the accumulation rapidly rises again as doctors gain experience with CT technology by participating in scanning activities. Similarly, while technicians learn little prior to the staffing change, following the rotation of inexperienced doctors through the CT area, technicians accumulate diagnostic knowledge.

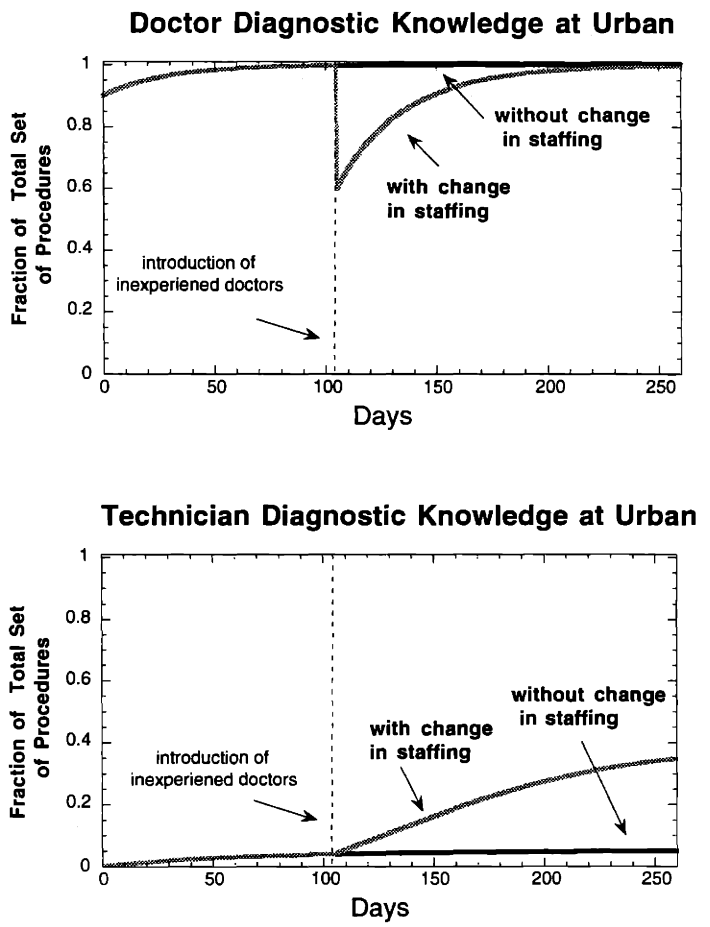


Figure 2.16: Diagnostic knowledge at Urban (using the full model)

In contrast to the experience of Suburban, Urban's staffing change does not lead to doctors' withdrawal from scanning operations because, the non-collaborative division of labor pattern that preceded the staffing change prevented technicians from accumulating appreciable diagnostic knowledge. Thus, when inexperienced doctors arrive in the unit, there are few occasions of role reversal (see Figure 2.17), so doctors remain in the CT area.

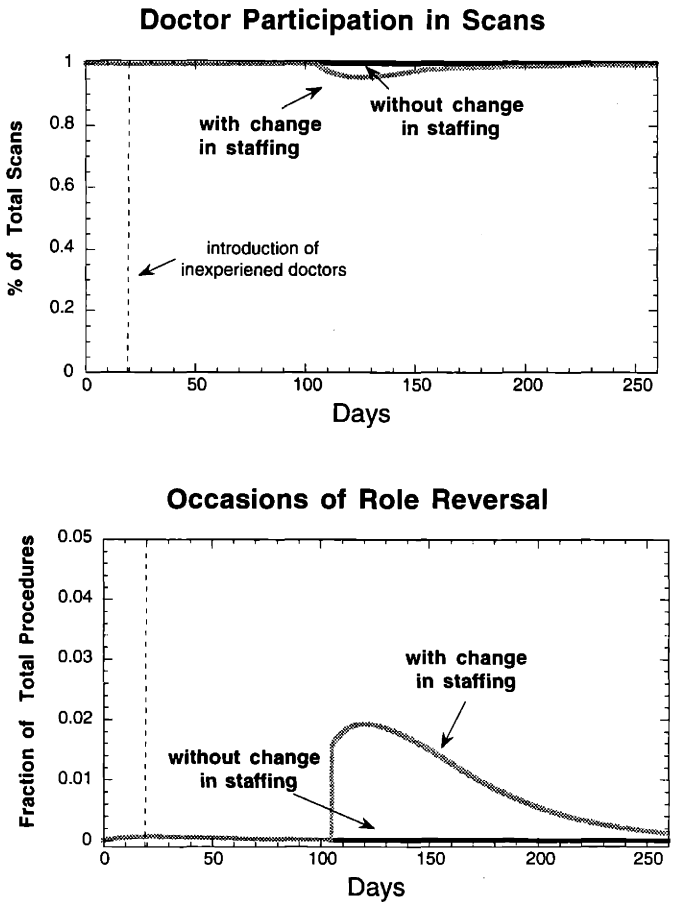


Figure 2.17: Doctor participation and role reversals at Urban (using the full model)

By participating in scanning, inexperienced doctors both learn rapidly and allow technicians to continue learning, thereby reinforcing the collaborative division of labor pattern.

We can summarize the outcomes of the staffing changes by saying that in Suburban's case the relative change in the levels of diagnostic knowledge challenges the institutionalized social order, and in Urban's it does not. When the relative accumulation of diagnostic knowledge favors the technicians, as in Suburban's second phase, both technicians and doctors act in ways to reduce or alleviate the challenge to doctors' status. Since we posit CT scanning as

a technology that *requires* collaboration for effective use, we suggest (even though Barley did not) that this uncollaborative division of labor is dysfunctional, as evidenced in simulations by stagnating, rather than growing, accumulations of knowledge for both groups. In contrast, when the relative balance of diagnostic knowledge favors the doctors, and the relative balance of operational knowledge favors the technicians, as in Urban's final phase, the resulting interactions do not challenge the existing social order thereby allowing both doctors and technicians grow and collaborate from their respective expertise.

2.5 Discussion

In scanning technologies that preceded CT, the division of labor was clear: technicians produced the scans, and doctors interpreted them. With procedures such as X-ray, technicians required no diagnostic understanding in order to competently create scans, and in fact technicians often could not recognize even rudimentary elements of pathology (Barley, 1986, 1988b). Doctors, on the other hand, usually had some knowledge of how to operate scanning equipment, though they seldom exercised it. With the introduction of computer-dependent imagery, however, the clear separability between scanning and diagnosis begins to disappear. Computed tomography, like ultra-sound technology, differs from X-ray in that it provides much more complicated, three-dimensional images of the human body and so requires a greater knowledge of what the scan reveals in order to assess its quality. A competent technician must therefore acquire some diagnostic knowledge in order to produce images that aid the doctor in providing an accurate diagnosis.

We can see the deployment of the computed tomography machine as "an occasion of structuring" that challenges the traditional division of labor. As a new "collaborative" technology, CT causes doctors and technicians to interact in ways different from their previous experiences. In the case at hand, the clear division of abilities and inclinations across the doctor-technician boundary–technicians produce scans, doctors evaluate them–did not support the new technology; moreover, these abilities and inclinations had to change to generate the benefits that the technology offered. Our inductive analysis of Barley's data suggests that more collaborative outcomes emerge when both groups have relatively balanced expertise or accumulations of capital that the new technology requires. If a new technology demands cross-boundary collaboration, then participants on either side of the boundary must be able to use it with similar degrees of competence.

For example, at the beginning of Phase 1 in Suburban and Phase 4 at Urban, the relative difference in accumulated operating knowledge (capital) between doctors and technicians are small. Under these circumstances technicians converse with doctors while conducting scans, and doctors can share their "preferences" for performing scans in particular ways. Through this "technical consultation" with doctors, technicians learn to recognize pathology and improve their ability to produce a useful scan. Likewise, when doctors watch the technicians operating the CT machine, and sometimes "mutually execute" a scanning procedure, they also accumulate operational knowledge that allows them to fine-tune the images in order to provide a better diagnosis. It is in these two phases that we find scripts like "preference stating," "technical consultation," and "mutual execution" that suggest a collaborative outcome (see Table 2.1).

When there is a significant difference in the relative accumulations of operating knowledge, however, "uncollaborative" patterns emerge. For example, in Phase 1 at Urban

doctors know more than technicians about operating the CT machine and feel obligated to run the machines themselves. Technicians regard the "usurpation as an emotionally charged event that signified disregard"(Barley, 1986: 96), and doctors infer that technicians make no attempt to learn (Barley, 1986: 97). Even though technicians complain to each other vociferously, they have little recourse with which to challenge the doctors' behavior, since they occupy a lower hierarchical status in the hospital. This action by the doctors clearly limits the possibility of collaboration and occasions a set of interactions that "constructs ineptitude" among the technicians.

A different but equally problematic pattern arises in the later phases of Suburban, where technicians have accumulated a significant amount of operating and diagnostic capital before the inexperienced doctors rotate into the area. Technicians instruct the new doctors "clandestinely," which suggests all parties recognize that technicians' knowing more about CT diagnosis than the doctors is "against the rules." Both doctors and technicians become uncomfortable and converse in ways to minimize clear demonstration of "role reversal." When technicians' repeatedly question the doctors' decisions, the traditional social order is challenged. Eventually doctors respond by retreating to their office, shutting the door, and closing the blinds (Barley, 1986: 94). Unlike technicians, when doctors feel threatened, they can use their power in the institutionalized social order to avoid activities (such as remaining in the scanning room). In the first case, the significant difference in operating capital favoring doctors challenges only a functional division of labor (technicians are expected to run the machine). In the second, the relative difference in operating and diagnostic capital favoring technicians not only challenges a functional boundary (doctors are expected to render diagnosis), but also—and more problematically—threatens a hierarchical boundary (doctors are expected to be in charge).

Simulating a simple model representing these interactions between accumulations of different types of capital and activities across the functional and hierarchical boundaries in CT units, we observe that the relationships modeled are sufficient to generate the organizational outcomes that Barley observed. Further, by making explicit the relative accumulations of capital and the activities that further constrain or enable future accumulations we discern how, through time, the different patterns of collaboration and non-collaboration evolved. With this understanding we can begin to theorize more broadly about other empirical settings and how activities generate and affect the accumulations of various types of capital and the extent to which the participants involved either conserve or transform the existing functional or hierarchical boundary (i.e., social order).

This analysis leads to two propositions regarding the introduction of new technologies that disrupt the customary division of labor by blurring separability of tasks:

P1: When relative differences in accumulations of expertise to use a new cross-boundary technology are small, then participants across the boundary will engage in activities and interactions that increase the possibility of collaboration using the technology.

P2: When relative differences in the accumulations of expertise to use a new cross-boundary technology are large, then participants will engage in activities and interactions that challenge not only functional but also hierarchical boundaries, which reduce the possibility of collaboration using the technology.

Attending to relative accumulations of the participants' expertise in using a new technology stands out as an important feature for empirical study in other settings. While the value of training is generally appreciated, current discussions primarily focus on moving individuals from novice to expert status. The more complicated issue of how training might create knowledge that then challenges functional and hierarchical boundaries has received scant attention. When introducing a new collaborative technology, relative expertise among groups

participating in it should be developed so that it does not lead to interactions that subvert roles and identities that the organization still requires and seeks to preserve.

2.6 Conclusion

The end of our effort is the beginning of a formal theory describing why collaboration across boundaries may and may not occur when a new technology is deployed. The first insight developed here is that collaboration often demands that current functional or hierarchical relations between participants be transformed to some degree in order to generate the benefits that such collaboration across boundaries promises The second insight is that whether the structuring processes occasioned by a new technology enable this transformation depends critically on the relative balance of expertise and whether or not that balance is congruent with the roles and aspects of the social order that the organization seeks to preserve. As Barley's case highlights, a traditional hierarchical boundary cannot always be immediately transformed by simply hiring people with expertise in a new technology. Instead, transformation is a more gradual, dynamic process that only works in a productive fashion if the initial accumulations of knowledge do not lead to interactions that challenge more deeply seated norms and values.

Beyond the implications for understanding collaboration, we have also tried to demonstrate that theories of structuration can benefit from application of the system dynamics method, and system dynamics can be guided by theories of structuration in dealing with challenging questions. The "grammar" of system dynamics for representing the activities, accumulations, and dynamic recursions (feedback) that interconnect them offers a practical method for representing and analyzing theories of structuration. With its emphasis on context-

specific details and internally generated behavior arising from recursive dynamics, simulation provides a tool to complement rich ethnographic work applying the structuration perspective. When placed in the context of important social theories, the process of modeling can focus and refine key issues that can propel theorizing forward.

Appendix to Chapter 2: Model documentation

The model was constructed in Vensim®, and the simulations described in Chapter 2 were produced using the following command file.

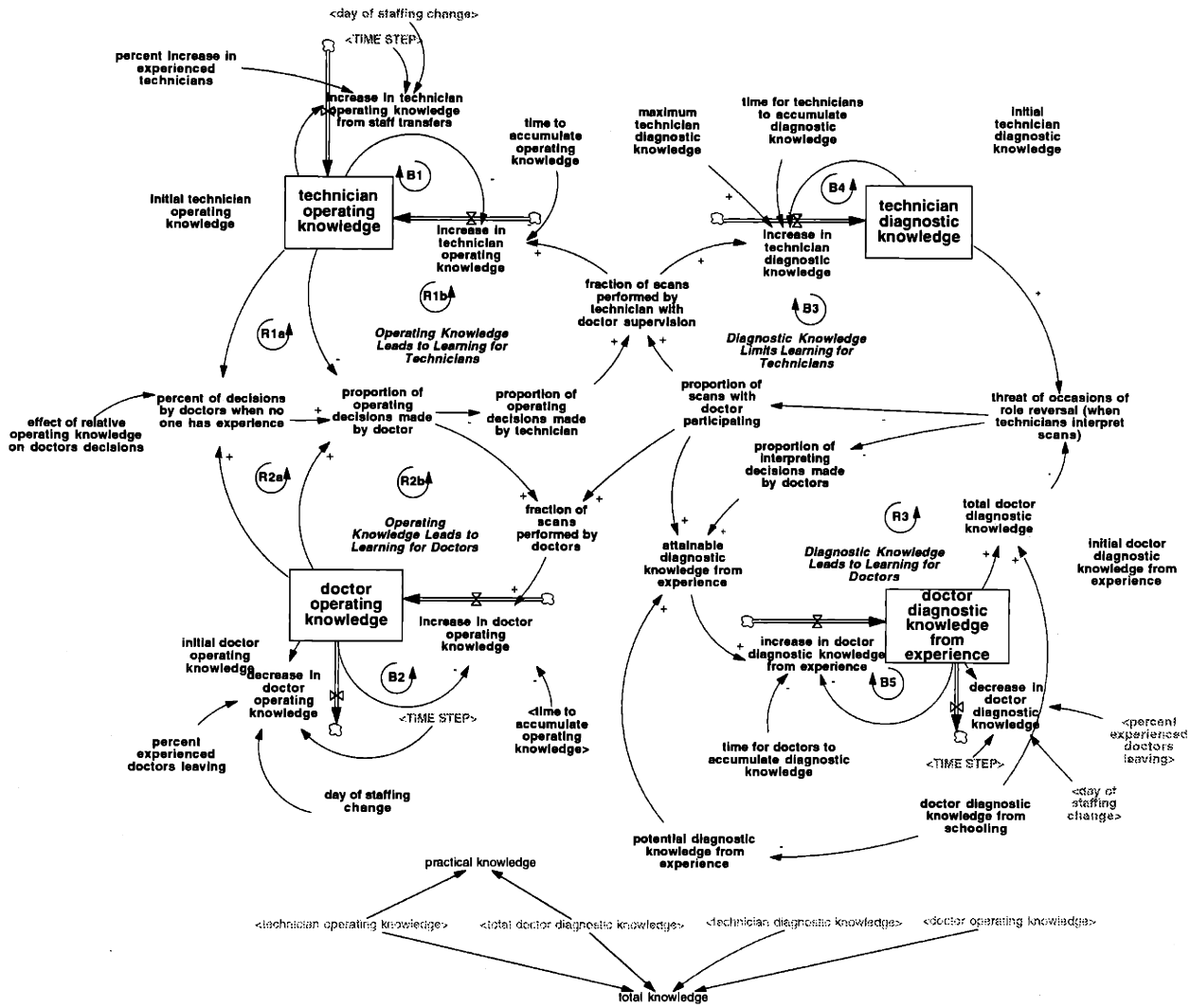
```
SIMULATE>SETVAL|initial technician operating knowledge=.3
SIMULATE>SETVAL|initial doctor operating knowledge=.5
SIMULATE>SETVAL|initial technician diagnostic knowledge=0
SIMULATE>SETVAL|initial doctor diagnostic knowledge from experience=.4
SIMULATE>SETVAL|day of staffing change=21
SIMULATE>SETVAL|percent experienced doctors leaving=.83
SIMULATE>SETVAL|percent increase in experienced technicians=0
SIMULATE>RUNNAME|suburban
MENU>RUN|o

SIMULATE>SETVAL|initial technician operating knowledge=.3
SIMULATE>SETVAL|initial doctor operating knowledge=.5
SIMULATE>SETVAL|initial technician diagnostic knowledge=0
SIMULATE>SETVAL|initial doctor diagnostic knowledge from experience=.4
SIMULATE>SETVAL|percent experienced doctors leaving=.83
SIMULATE>SETVAL|day of staffing change=1000
SIMULATE>SETVAL|percent increase in experienced technicians=0
SIMULATE>RUNNAME|suburban--nointervene
MENU>RUN|o

SIMULATE>SETVAL|initial technician operating knowledge=.1
SIMULATE>SETVAL|initial doctor operating knowledge=.5
SIMULATE>SETVAL|initial technician diagnostic knowledge=0
SIMULATE>SETVAL|initial doctor diagnostic knowledge from experience=.4
SIMULATE>SETVAL|date of doctors withdrawing from scans=28
SIMULATE>SETVAL|day of staffing change=105
SIMULATE>SETVAL|percent experienced doctors leaving=.8
SIMULATE>SETVAL|percent increase in experienced technicians=.5
SIMULATE>RUNNAME|urban
MENU>RUN|o

SIMULATE>SETVAL|initial technician operating knowledge=.1
SIMULATE>SETVAL|initial doctor operating knowledge=.5
SIMULATE>SETVAL|initial technician diagnostic knowledge=0
SIMULATE>SETVAL|initial doctor diagnostic knowledge from experience=.4
SIMULATE>SETVAL|date of doctors withdrawing from scans=28
SIMULATE>SETVAL|day of staffing change=1000
SIMULATE>SETVAL|percent experienced doctors leaving=.8
SIMULATE>SETVAL|percent increase in experienced technicians=.5
SIMULATE>RUNNAME|urban-nointervene
MENU>RUN|o
```

A full model diagram appears below. Equations for the model follow.



(01) attainable diagnostic knowledge from experience=
potential diagnostic knowledge from experience*
proportion of scans with doctor participating
*proportion of interpreting decisions made by doctors
Units: dimensionless
The CT-specific knowledge that doctors can acquire by observing how \ to use the CT machine to produce scans whose interpretation aids diagnosis of pathology

(02) day of staffing change=
1000
Units: Days
Day on which radiologists inexperienced with CT begin rotating through the CT unit

(03) decrease in doctor diagnostic knowledge=
((doctor diagnostic knowledge from experience*percent experienced doctors leaving)/ TIME STEP)*PULSE(day of staffing change,TIME STEP)
Units: 1/Day
The collective decrease in doctors' understanding of how to interpret CT scans, which results from experienced radiologists leaving and inexperienced doctors entering the area when there is a staffing change

(04) decrease in doctor operating knowledge=
((doctor operating knowledge*percent experienced doctors leaving)/TIME STEP) *PULSE(day of staffing change,TIME STEP)
Units: 1/Day
The collective decrease in doctors' understanding of how to produce scans using the CT machine, which results from experienced radiologists leaving and inexperienced doctors entering the area when there is a staffing change

(05) doctor diagnostic knowledge from experience=
INTEG (increase in doctor diagnostic knowledge from experience-
decrease in doctor diagnostic knowledge,
initial doctor diagnostic knowledge from experience)
Units: dimensionless
The CT-specific knowledge that doctors have about how to interpret a CT scan, acquired from on-the-job experience in this unit or from a previous rotation

(06) doctor diagnostic knowledge from schooling=
0.5
Units: dimensionless
The general diagnostic knowledge that doctors possess, regardless of whether they have had experience with the CT scanner

(07) doctor operating knowledge=
INTEG (+increase in doctor operating knowledge-decrease in doctor operating knowledge,initial doctor operating knowledge)
Units: dimensionless
The accumulated expertise that doctors have about how to use the CT machine to produce a scan

(08) effect of relative operating knowledge on doctors decisions
([(0,0)-(1,1)],(0,0),(0.05,0),(0.1,0.01),(0.2,0.05),(0.3,0.15),(0.4,0.333),(0.5,0.5),(0.6,0.666667),(0.7,0.85),(0.8,0.95),(0.9,0.99),(0.95,1),(1,1))
Units: dimensionless
A function suggesting the nonlinear effect of relative expertise in using the CT machine (doctors' relative to the sum of what doctors and technicians know together) on the percentage of decisions about how a scan should be conducted that doctors choose to make themselves rather than delegate to technicians\!\!

(09) FINAL TIME =
260
Units: Days
The final time for the simulation, based on the duration of the ethnographic study.

(10) fraction of scans performed by doctors=
proportion of scans with doctor participating*
proportion of operating decisions made by doctor
Units: dimensionless
The percentage of decisions about how to conduct scans that doctors make, suggesting that while technicians may be present (they do not have autonomy to leave the scanning area), only doctors operate the CT machine

(11) fraction of scans performed by technician with doctor supervision=
proportion of scans with doctor participating*
proportion of operating decisions made by technician
Units: dimensionless
The percentage of decisions about how to conduct scans that technicians make while doctors are present in the CT area, suggesting that technicians and doctors can discuss options and the rationale for trying different things to produce a scan useful to diagnosis, although only technicians operate the CT machine

(12) function for effect of technicians' diagnostic knowledge on doctor participation
([(0,0)-(0.1,1)],(0,1),(0.0148276,0.982759),(0.0241379,0.925287),
(0.0313793,0.747126),(0.0382759,0.528736),(0.05,0.2),(0.0596552,0.0632184),
(0.075,0),(0.1,0),(0.5,0),(1,0))
Units: dimensionless

A function suggesting the nonlinear effects that technicians' possession of diagnostic knowledge has on doctors' willingness to be around technicians who seem to possess expertise that doctors should have but do not

(13) increase in doctor diagnostic knowledge from experience=
MAX(0,(attainable diagnostic knowledge from experience-doctor diagnostic knowledge from experience)/time for doctors to accumulate diagnostic knowledge)
Units: 1/Day

The rate at which doctors learn about interpreting CT scans from on-the-job experience

(14) increase in doctor operating knowledge=
MAX(0,(fraction of scans performed by doctors-doctor operating knowledge)
/time to accumulate operating knowledge)
Units: 1/Day

The rate at which doctors learn about how to use the CT machine to produce scans (doctors learn by using the machine to produce scans)

(15) increase in technician diagnostic knowledge=
MAX(0,(maximum technician diagnostic knowledge*fraction of scans performed by technician with doctor supervision-technician diagnostic knowledge)/
time for technicians to accumulate diagnostic knowledge)
Units: 1/Day

The rate at which technicians learn about how to interpret CT scans (technicians gain diagnostic knowledge when doctors talk to them about the scans and provide rationale for conducting the scans in certain ways; there is a limit to how much technicians can learn about diagnosis, since they lack the rigorous and extended training of medical school and residency, so technicians can never gain as much diagnostic knowledge as doctors)

(16) increase in technician operating knowledge=
MAX(0,(fraction of scans performed by technician with doctor supervision-technician operating knowledge)/time to accumulate operating knowledge)
Units: 1/Day

The rate at which technicians learn about how to use the CT machine to produce scans that aid diagnosis (technicians gain operating knowledge by using the machine and exercising discretion in how to conduct the scans)

(17) increase in technician operating knowledge from staff transfers=
(technician operating knowledge*percent increase in experienced technicians/ TIME STEP)*PULSE(day of staffing change,TIME STEP)
Units: 1/Day
The rate at which technicians collectively gain knowledge about using the CT machine from having experienced technicians transferred into the unit or inexperienced technicians transferred out of the unit

(18) initial doctor diagnostic knowledge from experience=
0
Units: dimensionless
The amount of CT-specific expertise in interpreting scans that doctors (staffing the CT area when the new machine is deployed) have accumulated from on-the-job experience outside the CT unit under study

(19) initial doctor operating knowledge=
0
Units: dimensionless
The amount of expertise about how to operate the new CT machine that doctors staffing the CT area have when it is initially deployed (knowledge accumulated from experiences preceding the period of the CT unit under study)

(20) initial technician diagnostic knowledge=
0
Units: dimensionless
The knowledge about how to interpret CT scans to diagnose pathology that technicians staffing the CT area when the machine is first deployed have (accumulated from experiences outside the CT unit under study)

(21) initial technician operating knowledge=
0
Units: dimensionless
The amount of expertise about how to operate the CT machine that technicians staffing the CT area have when the machine is initially deployed (this expertise would have been accumulated from experiences outside the CT unit under study)

(22) INITIAL TIME =
0
Units: Days
The initial time for the simulation.

(23) maximum technician diagnostic knowledge=
0.4
Units: dimensionless
The most CT-specific diagnostic knowledge that technicians can accumulate from on-the-job experience (considerably less than 1, since they have little formal medical training and probably very little diagnostic experience using other tools)

(24) percent experienced doctors leaving=
0
Units: dimensionless
The fraction of the radiologists leaving the CT unit when there is a staffing change

(25) percent increase in experienced technicians=
0
Units: dimensionless
The collective knowledge gained when technicians least experienced in CT scanning are transferred out of the CT area or when technicians more experienced with CT scanning are transferred into the CT area

(26) percent of decisions by doctors when no one has experience=
effect of relative operating knowledge on doctors decisions (ZIDZ(doctor operating knowledge,(doctor operating knowledge+ technician operating knowledge)))
Units: dimensionless
The percent of decisions about how a scan should be conducted that doctors make when neither doctors nor technicians present have experience in how to use the machine to achieve a useful image, based on doctors' knowledge relative to what doctors and technicians know together (in other words, if doctors do not know much about using the machine, but technicians know less, doctors will make almost all the operating decisions, and if doctors know a lot but technicians know just as much, then doctors will cede many operating decisions to technicians); the formuation generously assumes that doctors allow technicians to make all decisions for which they are competent (and generously assumes that doctors perceive accurately what technicians know)

(27) potential diagnostic knowledge from experience=
1-doctor diagnostic knowledge from schooling
Units: dimensionless
The percentage of total diagnostic knowledge that doctors must learn from on-the-job experience using particular technologies, rather than from medical training

(28) practical knowledge=
(technician operating knowledge+total doctor diagnostic knowledge)/2
Units: dimensionless
The sum of expertise brought to bear on a patient in the CT scanning area congruent with the expected division of labor (that is, when technicians operate the CT machine and doctors interpret the scans), relative to potential; the sum of their respective knowledge accumulations, divided by the number of knowledge accumulations

(29) proportion of interpreting decisions made by doctors=
1-"threat of occasions of role reversal (when technicians interpret scans)"
Units: dimensionless
The percentage of all decisions about how to interpret the CT scans made by doctors rather than technicians

(30) proportion of operating decisions made by doctor=
doctor operating knowledge*(1-technician operating knowledge)+
(1-technician operating knowledge)*(1-doctor operating knowledge)*
percent of decisions by doctors when no one has experience
Units: dimensionless
The percentage of decisions about using the CT machine to produce scans made by doctors, based on the notion that doctors make decisions when they possess operating knowledge that technicians do not have and doctors also make a percentage of decisions about things for which neither technicians nor doctors have experience

(31) proportion of operating decisions made by technician=
1-proportion of operating decisions made by doctor
Units: dimensionless
The percentage of all decisions about how to use the CT machine to produce a scan made by technicians rather than doctors (technicians make decisions only when the doctors present delegate decisions to them)

(32) proportion of scans with doctor participating=
Smooth(function for effect of technicians' diagnostic knowledge on doctor participation
("threat of occasions of role reversal (when technicians interpret scans)"),4)
Units: dimensionless
The fraction of time doctors are in the CT scanning room while scans are being produced

(33) SAVEPER =
TIME STEP
Units: Days
The frequency with which simulation output is stored.

(34) technician diagnostic knowledge=
INTEG (increase in technician diagnostic knowledge,
initial technician diagnostic knowledge)
Units: dimensionless
The accumulated expertise about how to read CT scans to diagnose pathology that technicians gain from on-the-job experiences of operating the CT machine while talking with doctors about what they're doing and why

(35) technician operating knowledge=
INTEG (increase in technician operating knowledge+
increase in technician operating knowledge from staff transfers,
initial technician operating knowledge)
Units: dimensionless
The accumulation of expertise technicians have about how to operate the CT machine to produce a scan useful to diagnosis, increased by experience using the machine when doctors are present to provide rationale for trying certain maneuvers

(36) "threat of occasions of role reversal (when technicians interpret scans)"=
technician diagnostic knowledge*(1-total doctor diagnostic knowledge)
Units: dimensionless
The probability that technicians possess CT-specific diagnostic knowledge that doctors do not and so by interpreting scans may up-end the hierarchical and social norm that doctors should know more than technicians

(37) time for doctors to accumulate diagnostic knowledge=
28
Units: Days
The amount of on-the-job time needed for doctors to learn from on the job experiences interpreting CT scans

(38) time for technicians to accumulate diagnostic knowledge=
56
Units: Days
The amount of on-the-job time needed for technicians to learn from on-the-job experiences of producing and reading scans to diagnose pathology (because technicians have little formal medical training, it is assumed they take at least twice as long as doctors to learn diagnostic skills from looking at CT scans)

(39) TIME STEP =
0.25
Units: Days
The time step for the simulation.

(40) time to accumulate operating knowledge=
28
Units: Days

The amount of on-the-job time it takes to learn from on-the-job experiences using the CT machine to produce scans useful to dianosis (it is assumed that technicians and doctors learn at about the same rate, given the same experiences)

(41) total doctor diagnostic knowledge=
MIN(1,doctor diagnostic knowledge from experience+
doctor diagnostic knowledge from schooling)
Units: dimensionless

The total diagnostic expertise that doctors bring to bear in interpreting a CT scan (the sum of diagnostic knowledge gained from medical training and experience using other technologies and the diagnostic experience gained from on-the-job experience using the new CT technology

(42) total knowledge=
(doctor operating knowledge+technician operating knowledge+
technician diagnostic knowledge+total doctor diagnostic knowledge)/4
Units: dimensionless

The total accumulation of knowledge (relative to potential) in the CT area staff, including doctors' and technicians' knowledge of how to operate the CT machine and doctors' and technicians' knowledge of how to interpret scans (the sum of 4 knowledge accumulations, divided by the number of knowledge accumulations summed)

Chapter 3
A Framework Integrating Theories Relevant to Collaborating Across Boundaries

Chapter 1 emphasized that the need for working across boundaries often arises from interdependent work and that unexpected patterns of interaction may emerge during cross-boundary interactions. Chapter 2 proposed a theoretical lens drawing on three existing themes in social and organizational theory—daily activities, actors' accumulated resources, and the recursive relationships between these—and used that lens to explore *why* different patterns of interaction emerged between doctors and technicians when a new scanning technology was deployed at two similar hospitals. The exploration of Barley's (1986) ethnography of computed tomography (CT) scanning suggests that attention to cross-boundary activities and the recursive feedback processes in which they are embedded provides explanatory power for why (un)collaborative patterns evolve.

But the doctor-technician interactions over new technology comprised a cross-boundary interaction that was highly constrained in many respects. There was no confusion about who should be working together; both doctors and technicians were hired and present. There was a single tool, the new CT machine, and there was no question but its use was to produce scans to aid diagnosis of patient pathology. There was a single place where this doctor-technician interaction could take place in each hospital, and the timing of doctors' and technicians' working together was not debatable; a scan was to be produced and interpreted when a patient appeared for testing. The primary variables in the interaction were whether doctors participated in

producing the scan (technicians did not have autonomy to leave) and who actually operated the CT machine.

Not all cross-boundary interactions are so narrowly defined. More commonly, someone possesses a range of choice regarding who is involved, where the interaction takes place, what tools are used, and how. In this chapter I build on what was learned in the previous chapter to elaborate on and extend the activities – accumulations – recursion lens into a framework capable of accounting for more complex, less specified cross-boundary interactions. I describe how actors can increase their accumulated resources for their *own* work or for the work of *others* across the boundary. I elaborate on recursive dynamics by discussing actors' abilities and inclinations to *participate* in cross-boundary activities and the *accessibility* of the activities to their customary ways of knowing and doing their work. I describe four dimensions of cross-boundary activities—*artifacts* and the *actions* people take with them, *locations,* and the *timing* of activities in the flow of work —that influence accessibility and participation. My intent is not to create a new theoretical lens but to build on the one proposed by integrating research relevant to cross-boundary work from studies in cognition, knowledge management and knowledge representation, product development, and innovation. Uniting these theories in a more comprehensive framework for knowing and doing work consistent with dynamic theories of structuration and practice deepens the explanatory power of the activities – accumulations – recursion themes.

Section 3.1 provides an overview of the expanded framework. Section 3.2 provides context for the sections that follow by taking a step back to look at research on within-practice knowledge creation. Section 3.3 then discusses across-practice knowledge creation and elaborates on the activities – accumulations – recursion lens as described above. Section 3.4

briefly recapitulates the framework and describes how its elements help explain the emergence or absence of collaboration in interdependent work.

3.1 Overview of an expanded framework for cross-boundary work

The elaborated framework is summarized by the diagram in Figure 3.1. Continuing with the previous chapter's focus on practical know-how as a key form of capital, it includes a focus on *accumulations of knowledge* (represented by boxes) relevant to work on each side of the boundary (represented by the vertical bar in the center) and embodied in the participants in the interaction. Different boxes of knowledge indicate that participants bring different kinds of knowledge to interdependent work (one might think of specializations in functional expertise or divisions of labor across hierarchical lines). Their knowledge is not abstract but embedded in their abilities to *act* with or in response to specific *artifacts* in *locations* suitable and customary for their respective work, or practice. Participants bring knowledge of their own discipline and role to the cross-boundary activity, and through interactions at the boundary they can also acquire knowledge of others' work.

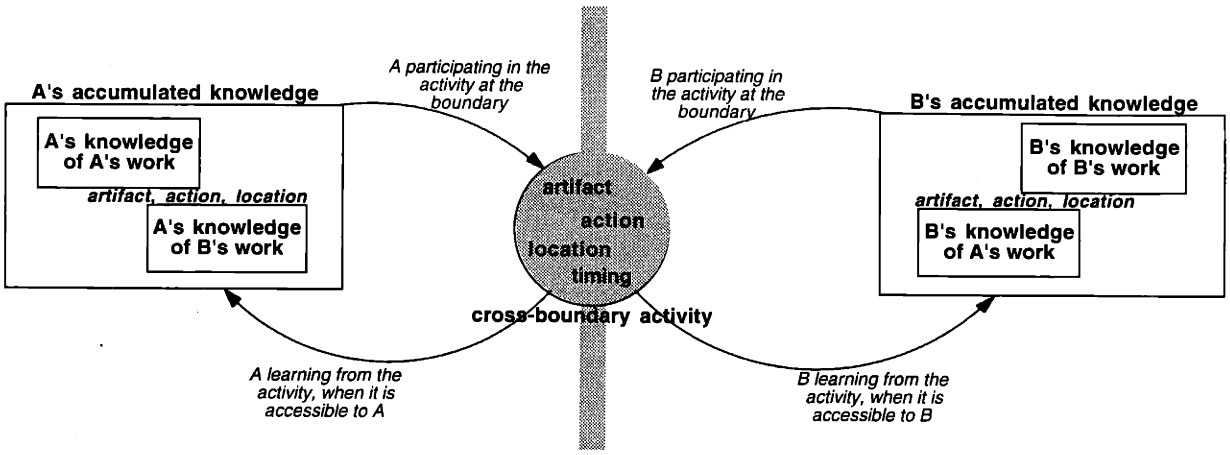


Figure 3.1 An expanded framework for examining cross-boundary interactions

The knowledge that participants accumulate shapes their *participation* in the cross-boundary activity (suggested by arrows pointing from the accumulations to the activity). A cross-boundary activity emerges as participants meet in a *location* that may resemble their workspace and take *actions* with *artifacts* at hand or prepared in advance to demonstrate their understanding of the work to other participants, whose knowledge differs. Because the *timing* of a cross-boundary interaction in the flow of work often influences where it takes place and the artifacts and actions possible, I include that as a dimension of the activity as well. Arrows pointing from the cross-boundary activity to accumulations of knowledge suggest that participants can *learn* from what unfolds during the interaction, if it is *accessible* to them. An activity is accessible to a participant to the extent that its artifacts, actions, and the location are congruent with the artifacts, actions, and locations customary to exercising the knowledge that he or she holds.

I call a cross-boundary activity "collaborative" when people on both sides of the boundary increase their knowledge about the interdependent work through participation in the

interaction. This does not mean that participants necessarily feel cordial or warm toward others during a collaborative pattern of working interdependently. It does suggest, however, that social patterns permit continued participation by all parties and allow participants at least periodic expression with tools and actions with which they are familiar in the settings that support their respective expertise.

In the sections that follow, I define the terms used above, anchoring them in the social and organizational theories from which they are drawn. I also elaborate on the relationships between elements and make a theoretical case for why each is necessary for constructing a framework with which to examine collaboration across boundaries. I discuss the dynamics of knowledge creation and renewal first within a given practice and then in cross-boundary work.

3.2 Within-practice knowledge creation

I take a pragmatic view of knowledge (Bourdieu and Wacquant, 1992; Carlile, 2002a), viewing knowledge as practical know-how, or competence to act. Within a given discipline or practice, knowledge can be viewed as an accumulation of understanding enabling people to act competently and thereby to gain more knowledge. This view has roots in theories of action and enactment (Goffman, 1959; Garfinkel, 1967; Weick, 1969/1979; Suchman, 1987), practice (Bourdieu, 1980/1990; Bourdieu and Wacquant, 1992) and structuration (Giddens, 1984), and cognition (Lave, 1988), knowledge management (Nonaka, 1994; Nonaka and Takeuchi, 1995; Leonard, 1995/1998), and organizational learning and communities of practice (Brown and Duguid, 1991; Wenger, 1998). This section first discusses each element in the cycle of

accumulation and action and then describes relationships between accumulations and actions in the context of people sharing a common practice.

Enacting

A focus on action and acting forms a critical element of the lens. Theorists such as Garfinkel (1967) and Goffman (1959) assert that individuals' and groups' *actions* prove a valid object of study because they reveal the social order in which those activities have meaning. Thus a social order can take shape through mundane activities in which individuals enact the common-sense knowledge necessary to act in "reasonable" ways and do "reasonable" things (e.g., Berger and Luckmann, 1966; Weick, 1969/1979). The meanings of actions thus emerge from moment-by-moment interactions between people, and between people and objects, in their surroundings (Suchman, 1987).

Many scholars of knowledge creation and apprehension give particular prominence to activities. Lave (1988) contends that individual cognition does not, as conventional cognitive theory maintains, reside wholly within one's head but rather is "seamlessly distributed across person, activity and setting" (1988: 171). Nonaka (1994) asserts that, although ideas may form in individual minds, interactions among individuals "contribute to the amplification and development of new knowledge" and that new learning is facilitated by people's sharing narratives and "war stories," participating in common experiences, and engaging in "continuous dialogue." Nonaka and Takeuchi (1995) elaborate that social interactions and social activities provide the primary mechanism for conveying and converting between tacit and explicit forms of knowledge and thus for creating new knowledge. Much of the recent scholarship on knowledge relies on the work of Polanyi (1966), who articulated the concept of tacit knowing, practical

know-how that resides in a person's body and its ability to perform certain actions competently without his necessarily being able to describe how he knows what he knows or how he executes his competence.

Capital and practices

Activities can generate enduring meaning because they lead to accumulation of resources, both tangible and intangible, whose influences can endure after the actions have ceased. Actions do not arise from abstract agents but from individuals participating in concrete and specific aspects of social practices (Dreier, 1999). Bourdieu refers to accumulations of "capital," whose value "...hinges on the existence of a game, of a field in which this competency can be employed: A species of capital is what is efficacious in a given field, both as a weapon and as a stake of struggle..." (Bourdieu and Wacquant, 1992: 98). This concept of capital[1] forms the basis of the lens's attention to accumulations of knowledge, reservoirs of understanding that encompass both declarative and tacit competencies. Leonard (1995/1998) also explicitly focuses on "wellsprings of knowledge," or cumulative repositories of know-how that reside in individuals, routines, and physical technologies within an organization. Knowledge capital cannot exist abstractly or isolated from a practice that values that knowledge (Bourdieu, 1980/1990). Thus knowledge capital consists of specific abilities to wield certain artifacts in particular settings suited to and supporting those activities. Furthermore, it takes shape within a practice, a set of assumptions about what is known and knowable, along with the values that give

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[1] This framework employs a concept of capital distinct from "social capital" (see P.S. Adler and S. Kwon, "Social Capital: Prospects for a New Concept," *The Academy of Management Review, 27* (2002): 17-40, for a summary of research on social capital). The notions of accumulation and differentiation among types of capital, explicit in Bourdieu's sociology (1980/1990, 1992) are not captured by social capital, considered more generally as "goodwill" and conceptualized as a function of the number of an entity's "ties" or relationships to others.

rise to those assumptions, and the tools and socially sanctioned actions that embed and represent those assumptions.

Knowledge creation and renewal

The literature exploring how individuals, groups, and organizations learn by doing (e.g., Epple, Argote and Devadas, 1991; see Yelle, 1979 for a review of learning by doing literature) relies on a model of activities leading to know-how and of knowledge, in turn, informing and manifesting itself in activities. The basic learning-by-doing model assumes that learning is cumulative, with knowledge accruing to the individuals, groups, or organizations who do the doing, and with the accumulated knowledge in turn informing further doing (Argote, 1999). It is thought to operate at all levels of learning, from the ideal type of the apprentice shadowing a master to organizations' dominating their markets by being the first to do and the fastest to learn. Leonard (1995/1998) states that core capabilities, repositories of knowledge accumulated over time and not easily imitated, must shape the activities that an organization undertakes: "[C]ore capabilities are created through knowledge-creating activities, but those activities are also dependent on, and enabled by, core capabilities" (Leonard 1998:4-5).

The iterative cycle of acting and accumulating knowledge is conspicuous in theories of learning among individuals and within groups sharing tasks. Wenger (1998) writes of "practice as learning" that emerges while individuals work together in communities that coalesce around joint enterprises and shared ways of accomplishing work. He asserts that negotiated meanings and shared understandings derive from the activities of mutually undertaken work. Similarly, Brown and Duguid's (1991) analysis of Orr's ethnography of service technicians attributes group knowledge as resulting from, and also giving rise to, social interactions: "The reps' work is not

simply about maintaining machines; it is also and equally importantly about maintaining social relations..." (1991:43). These ongoing social interactions lead the technicians observed to communal problem-solving, collaboratively building through time a shared repository of ways to tackle tricky problems, which in turn leads to more interactions.

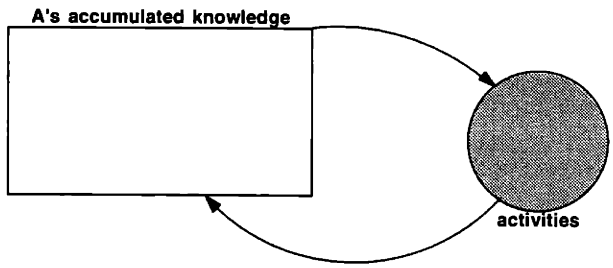

Figure 3.2: Within-practice knowledge creation and renewal

The theoretical model described above (portrayed in Figure 3.2) of activities generating knowledge, which in turn informs further action, resembles a substantive theory of knowledge akin to formal theories of structure and agency (Giddens, 1984) and of capital and habitus (Bourdieu, 1980/1990; Bourdieu and Wacquant, 1992) interacting through time. The lens proposed in Chapter 2 and expanded here builds on the notion that elements of know-how expressed in activities can influence enduring norms about what knowledge is and so in turn shape future actions. In this way, pragmatic knowledge is competence to engage in an activity and thereby gain more knowledge.

A few researchers explicitly draw on theories of structuration and practice in framing their work on organizational learning and knowledge. For example, Orlikowski (1992) frames individuals' action as taking place within a context in which the organization's accumulated values, knowledge, and other forms of "structure" influence how they appropriate new processes in daily activities. Drawing on Giddens' (1984) structuration theory in her study of consultants' implementing a software designed to enhance productivity, she notes, "The culture of the

workplace, managerial ideology, and existing bases of expertise and power significantly influence what technologies are deployed, how they are understood, and in which ways they are used" (1992:421-422). As another example, Pentland's (1992) study of software support help-desks proposes that individuals bring the organization's distributed expertise to bear on customer problems through "organizing moves" that both reflect and re-enact the company's structural features with respect to physical layout, ritual (particularly hierarchical) practices, and competency specializations. He draws on work by Bourdieu (1980/1990), Giddens (1984), and Lave (1988) to portray support-desk personnel as holding and acting on knowledge "contingent on performance, action, and outcomes...[that] only exists relative to a situation or a context" (Pentland, 1992: 529). Such research draws attention to recursive dynamics between in-the-moment activities and enduring organizational norms for getting work done within a particular department or role.

3.3 Across-practice knowledge creation

It is one thing to assert that social interaction leads to learning when individuals share a common practice—common assumptions, tools, activities, and locations. It is another to assume that the same kinds of interactions that engender learning within a practice will also lead to accumulating knowledge *across* domains of expertise. Since the view of interdependent work at the center of this study assumes that people bring different skills to the boundary, the theoretical framework proposed must address interactions at the boundary that may lead to people on either side increasing their knowledge of the work at hand. To elaborate on the summary presented diagrammatically in Section 3.1, I first discuss the nature of a boundary and reiterate the need for

interacting across them. I then elaborate on each element of the activities – accumulations – recursion lens (see Figure 3.3) used in Chapter 2 to enhance its explanatory power in a wider variety of circumstances of cross-boundary work. The elaboration defines two types of accumulated resources that can arise from cross-boundary work, two aspects of recursion between accumulated resources and cross-boundary activities, and four dimensions of cross-boundary activities.

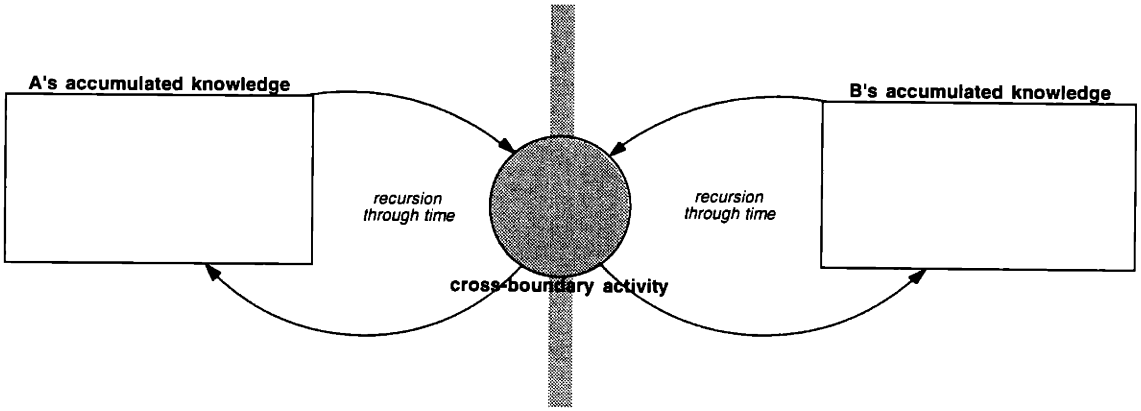

Figure 3.3: The activities – accumulations – recursion lens for examining cross-boundary work

Boundaries between practices

Boundaries are demarcated not so much by obstructions as by the absence of common pathways. They are "sites of difference," social or logical or geographic places where things on one side differ in some respect from things on the other (Abbott, 1995). In some cases, one can interpret the absence of common pathways literally: Conducting work at disparate locations creates a boundary that must be overcome spatially or temporally if interdependent work is to proceed. Regardless of whether location is shared, however, the absence of shared tools and shared activities creates boundaries, particularly because differing tools and actions reflect differing assumptions about what is important to "doing good work." These differences can

affect participants' abilities to act and interact with others across a boundary. One department may host meetings, keeping the conversation on "its turf." One group's work may precede another's, giving that group opportunity to make decisions first, with the expectation that subsequent work can adapt to the consequences of decisions already made. Because all actions are situated—that is, specific, local, and contingent upon moment-by-moment interactions between actors and between actors and objects in their surroundings (Suchman, 1987)—interactions at the boundary often favor one side's expressing its understanding of the work over the other's.

Who accumulates what knowledge

Because interdependent work necessitates that people work together, participants in a cross-boundary activity are expected to bring expertise specific to their role in the endeavor at hand. In new product development, marketing staff, design engineers, and manufacturing engineers bring distinctive expertise to shape the features, performance, and production processes for the new product (Henderson, 1991; Dougherty, 1992; Wheelwright and Clark, 1992; Carlile, 1997, 2002a). Sometimes participants are well prepared for their role in interdependent work, as were the physicians, discussed in Chapter 2, who were hired to deploy each hospital's new CT machine specifically because of their previous experience in working with or in researching scanning technologies. In other situations participants are ill-prepared, as were the technicians (at Urban hospital) transferred into the new unit without CT scanning experience or training on the new machine. Even though those technicians had little expertise, however, a specific kind of knowledge, ability to operate a machine to produce scans, was expected of them in keeping with their role of technician.

In addition to one's own practice- or role-specific knowledge, however, participants can also bring or acquire knowledge considered the realm of others, across the boundary (see Figure 3.4). This aspect of knowledge creation has been given less attention in the literature. But Barley's (1986) case described how CT-experienced doctors knew enough to operate the CT machine themselves and, by doing so, gained additional competence in an activity that might have been performed by technicians. Similarly, even though technicians at Suburban hospital did not know how to interpret CT scans when the machine was first deployed, by interacting with the experienced radiologist during the first three weeks, they gained sufficient diagnostic knowledge to challenge CT- inexperienced radiologists when they entered the unit during the fourth week.

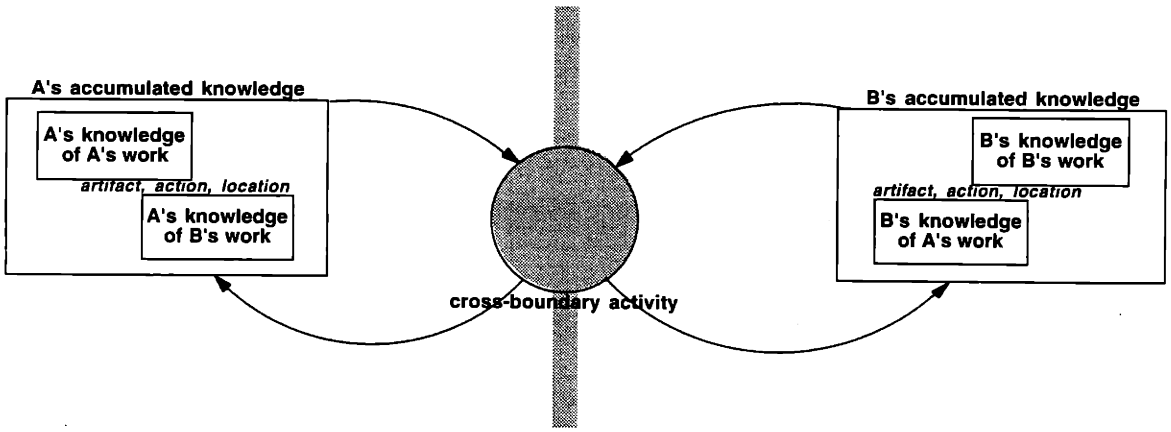

Figure 3.4: Two kinds of knowledge accumulations

Participation and accessibility in recursive dynamics

The lens suggests that accumulated knowledge informs activities and activities in turn lead to growing knowledge accumulations. Accumulated knowledge about cross-boundary activities influences how and the extent to which an actor can *participate* in interactions with others whose knowledge differs, and participants can *learn* about interdependent work from

cross-boundary activities to the extent that the activities are *accessible* to them, or familiar and resonant with their customary practices (see Figure 3.5).

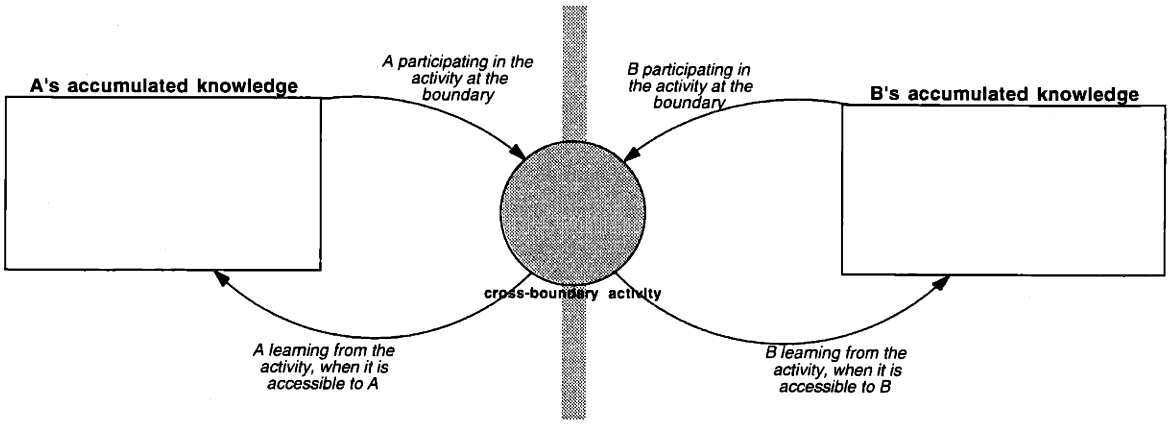

Figure 3.5: Recursion in participation and accessibility

Participating in cross-boundary activities

When people with different skills work together, they often begin by learning what the other can do, forming an understanding of how their cooperative work might proceed. In general terms posed by Berger and Luckmann,

> As *A* and *B* interact, in whatever manner, typifications will be produced quite quickly. *A* watches *B* perform. He attributes motives to *B*'s actions and, seeing the actions recur, typifies the motives as recurrent. As *B* goes on performing, *A* is soon able to say to himself, "Aha, there he goes again." At the same time, *A* may assume that *B* is doing the same thing with regard to him. From the beginning, both *A* and *B* assume this reciprocity of typification.... Thus a collection of reciprocally typified actions will emerge, habitualized for each in roles, some of which will be performed separately and some in common (1966:56).

As people interact, they form opinions and expectations about how to define the situation they share and their respective roles in it (Goffman, 1959). As people interact with an intent to collaborate, however, part of their interaction consists of revising their expectations about the division of labor—hence the cooperative aspect. In short, collaboration often requires people

whose knowledge differs to learn new things; at least they must learn how their understandings differ and specific ways in which each one's work depends on the other's.

Although the need to work across boundaries is stated implicitly in many writings on organizational expertise, it becomes explicit in studies of processes that by nature cross divisional lines, such as product development or innovation processes. Scholars and practitioners of innovation and product development have long advocated involving a wide variety of stakeholders throughout the process (e.g., Wheelwright and Clark, 1992, Ulrich and Eppinger, 1995). To ensure that new products meet customer needs, marketing and research-and-development functional expertise must be integrated (Griffin and Hauser, 1996). Product development teams must also include strong participation from manufacturing to assure that new products can be reliably assembled at reasonable costs (Ulrich and Eppinger, 1995; Smith and Reinertsen, 1998). Who participates in a project review affects which issues might be identified and the urgency with which they are viewed. The premise of widespread participation is that actively engaging people specializing in different skills in interdependent work is necessary to achieve the organizational goal, whether it is an efficient CT scanning unit, an information system effective for multiple municipal offices, or a high-quality new product.

Learning from accessible cross-boundary activities

A participant learns from a cross-boundary activity to the extent that it has characteristics congruent with her realm of expertise (Henderson, 1991; Carlile, 1997). Aspects of the interaction at the boundary are "accessible" to her when she can competently wield them in communicating with other participants. The notion of accessibility is akin to what Carlile (2002a) calls effective "boundary infrastructure," in which shared objects and activities represent

the knowledge of people on both sides of a boundary, as well as the dependencies in their work, and are transformable by all parties. To borrow Berger and Luckmann's generic terms, *A* can apprehend and learn more about the work at hand and her role in it when interactions with *B* allow her to represent what she knows about the effort using the language and objects she usually employs in doing the work. If *A* participates in an interaction at *B*'s location, in which *B*'s activities and artifacts are the focus, then *A* may not readily understand how her tools and methods (and therefore her knowledge) relate to and inform the work at hand. Then the interaction at the boundary is inaccessible to her. *B*'s dominance of the interaction, inadvertent or otherwise, can render *A* "incompetent," in that she cannot convey her knowledge with *B*'s artifacts, activities, and locations, which embody assumptions and methods different from *A*'s discipline.

It may be possible for *B*'s tools-of-the-trade to become more accessible to *A*, if *B* explains the method and reasoning instantiated in them and conveys his inferences about what conclusions he is drawing from their use during the interaction. In this way, by sharing reasoning and explaining inferences, *A* may learn how to use *B*'s methods in her work, or *A* and *B* may both learn or develop new methods with which to represent their work to one another. These kinds of explanatory interchanges often require some explicit attention to the process of working together, as well as iterative joint use of unfamiliar tools, methods, and assumptions. To explore further the notion of learning from accessible activities, it is necessary to be more specific about several dimensions of cross-boundary activities.

Dimensions of cross-boundary activities

From the literature I distill four dimensions of a cross-boundary activity that merit attention: the physical artifacts used, the actions people take with those artifacts, the locations where a cross-boundary activity takes place, and its timing within the flow of work (see Figure 3.6). These elements are, either explicitly or implicitly, identified in many methods for describing social situations or discerning cultural meanings from particular activities (e.g., Spradley, 1980). Actions take place in specific local settings with concrete artifacts wielded to serve particular purposes and are often designed to encourage certain trajectories of participation (Taylor, 1995; Dreier, 1999). Moreover, artifacts, actions, and locations can often play a significant role in clarifying misunderstanding and making a participant's tacit knowledge understandable to others and herself.

> Understanding is always against a background of what is taken for granted, just relied on.... When the misunderstanding stems from a difference of background, what needs to be said to clear it up articulates a bit of the explainer's background which may never have been articulated before (Taylor, 1995: 47).

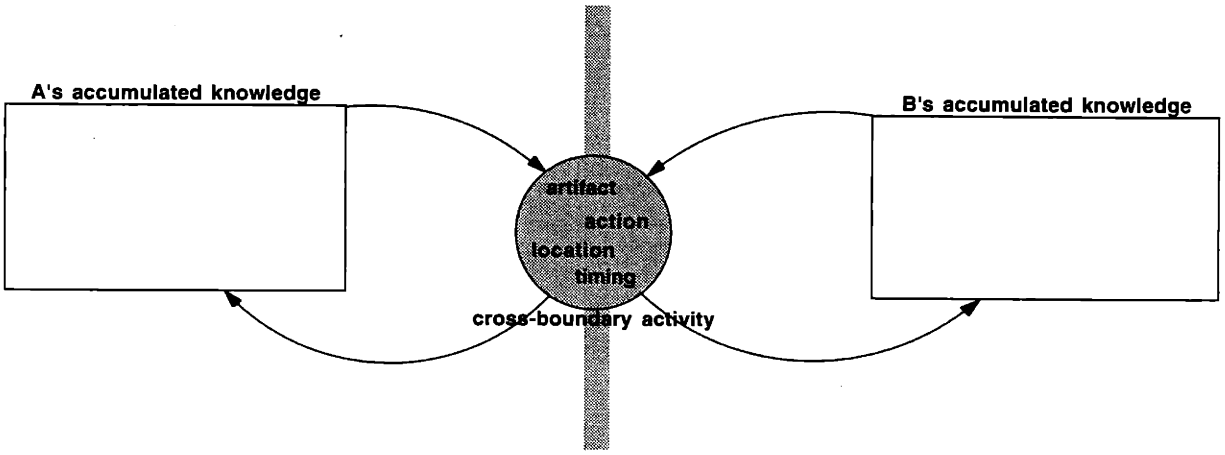

Figure 3.6: Four dimensions of a cross-boundary activity

Artifacts

Physical objects can play a significant role in focusing or diffusing the attention of participants. "Material artifacts set sensemaking processes in motion; sensemaking is constrained by actions, which themselves are constrained by artifacts" (Weick, 1990: 33). For example, the artifacts used in an interdepartmental review of a new product effort can influence which aspects of the product are most salient and thus what kinds of problems are identified. The very familiarity of some objects and tools can lead participants to overlook some of the assumptions embedded in them about how work gets done. Because an artifact is a physical manifestation of some method or procedure within a realm of expertise, identifying and employing artifacts usable and meaningful to participants holding disparate kinds of expertise can be challenging.

Star (e.g., Star and Griesemer, 1989) coined the term "boundary object" to refer to tools and objects useful in communicating across boundaries of department or role because they are ambiguous in some respect, supporting alternative interpretations or meanings to people on either side of a boundary. As people discuss an artifact that represents some aspect of their work, these alternative meanings—and their consequences to the work at hand—emerge and provoke additional conversation. Henderson (1991, 1998) studied the use of engineering sketches and prototypes and found that artifacts can serve as "conscription" devices as well, binding participants to a particular view of the matter at hand, perceived as embodied in the object, and organizing and enlisting their efforts in conformance. Carlile (1997) elaborated on Star's definition, suggesting that robust boundary objects useful in dealing with situations of novelty are those artifacts and tools that represent the different knowledge of the participants, portray their interdependencies, and are transformable by each participant.

Actions

Actions in cross-boundary interactions may be active or passive. Participants may merely listen, or they may ask questions and provide information and opinions. In product development, participants may only observe engineering drawings and prototype parts from a distance, or they may add their own sketches and assemble, disassemble, or deform parts. How people interact with each other and with the tools at hand also influences the issues identified during a cross-boundary interaction. As mentioned above, actions play a role in surfacing tacit knowledge (Polanyi, 1966; Nonaka, 1994) and in acquiring new skills (Argote, 1999). It is not always obvious, however, how to design activities capable of surfacing tacit knowledge in more than one realm of expertise. It is more likely that participants on one side of the boundary will dominate activities at the boundary, through familiarity with the location or artifacts at hand (Carlile, 2002b).

Locations

Researchers in innovation (Von Hippel, 1994) and cognition (Lave, 1988) highlight the role that location plays in practical know-how. In a cross-boundary interaction, participants most familiar with a location may have a stronger voice in the interaction. Tyre and Von Hippel (1997) assert that information "sticks" to locations—that is, is costly to move from one location to another—as they observe that problem-solving often iterates between the lab and the environment of use. Nuances of context influence the appearance of artifacts and actions that take shape in a given place and the ways participants can express their tacit knowledge. Tyre and Von Hippel argue that "theories of collaboration could be improved by taking into account that learning occurs not simply through human interaction, but through people interacting within

one or more particular physical contexts" (1997:73). Their study of teams addressing problems with the introduction of new technology to factories suggests not only that alternating problem-solving locations (between the factory and the lab) pushed resolution forward but also that different settings affected the social interactions that could occur.

Timing

When a cross-boundary activity occurs in the trajectory of work affects the nature of the interaction as well. Research in product development has long advocated involving stakeholders from across the organization in new product efforts *early* in the development cycle (e.g., Wheelwright and Clark, 1992; Thomke and Fujimoto, 2000). Early exposure and discussion within the organization can help identify problems in a project earlier in the development cycle, sometimes drastically reducing costs associated with their solution (Boehm, 1981; Thomke and Fujimoto, 2000). The timing of activities affects cross-boundary collaboration when it influences who can gain knowledge of the work at hand at that moment. Meetings among design, manufacturing, and marketing shift in the value they add to the product development cycle (Song, Thieme, and Xie, 1998), depending on how knowledgeably manufacturing can speak about production processes for parts that exist in only two-dimensional drawings, or depending on the extent of rework necessitated by marketing's stipulation for additional features. Pressure to produce in an ongoing stream of work can also affect participants' ability to engage in cross-boundary conversations, which may be seen as useful but not as urgent (Repenning and Sterman, 2001). Moreover, it is difficult to talk about the artifacts, actions, and locations of cross-boundary activities without giving explicit attention to the timing of the activities in the

flow of work, since progress in the work itself draws those artifacts and actions into existence or makes it appropriate to meet at some locations rather than others.

3.4 Summary

This framework builds on existing theories of cognition, knowledge management, and product development and innovation and unites them in a more comprehensive lens of knowing and doing work consistent with dynamic theories of structuration and practice. Taken together, the elements provide focus on the who, what, where, when, and how of cross-boundary work. Participants bring accumulations of knowledge distinct to their role to activities at the boundary in which the timing, location, artifacts, and actions influence their ability to represent their understandings and the differences they make to others' work. Participants learn more about interdependent work when activities are accessible to them, or congruent with at least some aspects of their ways of knowing and doing work. Recursive interactions of participation and learning between activities and accumulations of knowledge play out through time in collaborative patterns, through which all parties increase their knowledge of the work at hand, or in uncollaborative ways, in which learning by one or both parties is limited.

The value of the larger framework lies in strengthening and refining explanations of why particular patterns emerge in certain situations. Specifically, it points to three mismatches that can lead to uncollaborative patterns of cross-boundary interactions. First, there can be a mismatch between accumulated knowledge and expected role in the interaction. Uncollaborative patterns can emerge when participants on one side of a boundary accumulate knowledge considered the rightful purview of others across the boundary, as described in Chapter 2, when

technicians appeared to know more than doctors about interpreting CT scans and doctors withdrew to reduce the threat of role reversals. Second, a mismatch can occur across the boundary, when accumulations of expertise are congruent with role but imbalanced in level or amount. An example of this was also observed in the previous chapter, when inexperienced technicians frustrated experienced doctors, who then usurped the technicians' work. Third, mismatches between the location, artifact, and actions of a cross-boundary activity and a participant's practice can make that activity inaccessible to her and thus limit learning. The next chapter, investigating interdepartmental work during new product development, explores this last mode of failure in cross-boundary work.

In each of these situations, learning by one or both parties slows or ceases, stymying the ability of participants to work together and deepen their understanding of interdependent enterprises. These mismatches are interrelated through recursive feedback patterns that lie between participants' accumulated expertise and their ability and inclination to act in the shared space of cross-boundary activities. Nevertheless they are distinct. Remedies for mismatches between activities and a participant's customary practices might lie in redesigning the activities' location, tools, or timing or in reconsidering which participants are involved. Mismatches for imbalances in expertise to engage in interdependent work across a boundary might be addressed through training or staffing changes. Discrepancies between accumulated knowledge and expected roles in cross-boundary interactions might instead be alleviated through revisions to job descriptions, changes to standard operating procedures, or establishment of certification programs, all of which clarify and legitimate certain skills appropriate for certain roles. Thus the expanded framework's decomposition of accumulations, activities, and recursion permits us to

discern more precisely why patterns of interaction evolve as they do and to suggest more effective levers for producing collaborative patterns and the organizational outcomes desired.

Chapter 4
Interdepartmental Interactions in Product Development

4.1 Introduction

Product development processes cross departments, including marketing, engineering specialties, manufacturing, assembly, and often a host of staff functions ensuring that new goods and services meet internal cost targets and external governmental regulations. Scholars and practitioners agree that successful product development requires integration of knowledge from multiple functions. The challenge often lies in encouraging employees to bring their functional expertise to conversation and collaboration with people who know and value other kinds of knowledge, use different tools in daily work, and speak in discrepant vocabularies. In the press of turning an idea into a tangible good or service, the product development "team" often does not agree on what the next problem is, much less on its solution.

Proposed remedies for integrating work across functional lines include both people- and task-centered advice. Research on leadership and teamwork in product development calls for understanding the pros and cons of "lightweight," or more functionally focused, and "heavyweight," or more project-focused, teams (Wheelwright and Clark, 1995); adding generalists to balance specialist team members (Smith and Reinertsen, 1998); and ensuring that employee rewards encourage team, rather than individual, performance (Griffin, 1997). This line of inquiry also emphasizes the importance of early involvement of multiple functions in new product development (Khurana and Rosenthal, 1997) and knowing when to involve different

departments in which stage of new product work (Song, Thieme, and Xie, 1998). Other scholars take engineering-oriented tacks to managing product development tasks, including using tools such as the Design Structure Matrix to recognize and manage interdependencies among tasks (Ulrich and Eppinger, 1995), optimally overlapping design and manufacturing tasks (Krishnan, Eppinger, and Whitney, 1997) and adhering to structured methodologies and stage-gates for decision-making, from concept identification through production start (Ulrich and Eppinger, 1995; Griffin, 1997). These recommendations aid cross-functional integration by ensuring that people responsible for new product work recognize their interdependence and their respective responsibilities and so work together to prevent untimely surprises in development work from jeopardizing launch timing or product quality.

Even if an organization follows these recommendations, staffing teams appropriately and providing effectual organizational infrastructure, it remains unclear exactly what these people should *do* as they work together. The engineers should do the engineering obviously, and the manufacturing representatives should plan and execute production tooling, and members all around should keep each other "well informed." But how? In meetings, project updates, and prototype reviews, what do people who talk in different jargon and use different software and hardware *do* to establish common ground, shared vocabulary tools useful and usable to all participants involved?

Current approaches to cross-functional collaboration in product development often ignore the content and practices of work. They frequently do not discuss the efforts necessary to bridge those practices, efforts that often deteriorate in awkward pauses over drawings plain to some and mysterious to others or in attributions of other participants' ignorance or apathy regarding the work. Moreover, prescriptive approaches to product development processes often overlook the

emergent nature of the work. In many organizations product problems encountered late in the development cycle that result in unexpected cycles of re-design and re-testing, slipped production schedules, or warranty problems are the norm, or at least an ever-present danger.

In this chapter I build on current research on collaboration in product development by providing a descriptive account of the work content and actual practices in various departments at one manufacturing company. My goal is to analyze, qualitatively and through simulation, the micro-processes of creating and exercising knowledge about new product work through collaboration across boundaries. By simulating various scenarios of interdepartmental interactions, I explore the capabilities, conditions, and tools—and their timing—that sustain or undermine collaborative patterns among departments. The research question guiding the study is: Given that expertise is distributed throughout an organization, how do the nature and timing of interdepartmental activities bring that expertise to bear effectively on product development efforts? More generally, what aspects of joint activities effectively exercise expertise, distributed throughout an organization, in boundary-crossing work?

To explore this issue, I studied one organization's product development activities and the interdepartmental reviews that occasion knowledge creation and exchange about new product work. This study contributes to research on integration of cross-functional work and knowledge management by identifying two knowledge "mismatches" that take place at the firm (here called the Company), inhibiting collaborative interactions among departments. The first mismatch occurs between aspects of interdepartmental activities—specifically, their artifacts, actions, and locations—and the accumulated skills or practices of participants needing to become engaged in the new product work. This mismatch renders the review inaccessible to some participants, who learn little about the work at hand and so contribute little to its progress. The second mismatch

results from imbalance across the design-manufacturing boundary in how much people know about new product work, an imbalance that can suppress substantive interdepartmental conversation through most of the development cycle. Analyses suggest that sufficiently early reviews that engage plant personnel in identifying problems can increase the knowledge of both design and manufacturing early in the development cycle and keep people involved and productive in interdependent work.

Section 4.2 describes the data collection and analyses of the Company's product development process in general and the variety of cross-departmental reviews in particular. In Section 4.3 I outline findings from qualitative analyses, which suggest that reviews salient to manufacturing and assembly late in the development cycle contribute to sudden increases in identification of latent problems and changes to design shortly before launch. Section 4.4 presents a small dynamic model, grounded in the field data, that allows simulation of product development progress while varying the nature and timing of interdepartmental interactions. Section 4.5 describes findings from model analysis, particularly focusing on shaping and timing reviews to rebalance expertise across the design-manufacturing boundary to achieve the Company's goal of concluding design changes well before launch and on accounting for both mechanical and social aspects of cross-departmental work. Section 4.6 discusses why some tools and methods are useful in representing and exercising distributed expertise across the design-manufacturing boundary, as well as some practical aspects of staging reviews to rebalance relative expertise across departmental lines.

4.2 Data collection and analyses

Description of the field site

The organization at which I conducted this research manufactures motor vehicles and launches new models annually. A medium-size company (with about 7,000 employees), the Company has its headquarters, product development center, and two engine plants in one city, with vehicle assembly plants in other cities. In 2001 it produced more than 200,000 vehicles on five platforms in more than 30 models. With remarkable customer loyalty and a growing market, the Company has enjoyed enviable growth, particularly after having made significant improvements to its manufacturing processes in the late 1980s. In the1990s the Company began looking for ways to improve its product development to meet unsaturated demand, retain share in a market attracting competitors, and complement its plans for increasing production volumes.

Product development at the field site

The history of product development at the Company has a mixed character. Customers and employees alike express admiration for the products delivered, but the "firefighting" method of creating the products has been infamous within the Company. Manufacturing and assembly staff described prototype builds at the plant for which design engineers hand-carried hastily prepared parts. In the mid-1990s the vice-president of engineering expressed his belief that the pattern of frenzied activity in the weeks leading up to launch existed because engineers relished their role as "Marlboro men," heroes tough under pressure (Jones and Repenning, 1997). But employees have bemoaned, not celebrated, "late changes," alterations to new product designs in the weeks before launch. Late changes necessitate unexpected testing cycles, frustrate suppliers,

and strain production processes and tooling, raising costs, wasting resources, and fatiguing the organization. In one internal assessment, every product development stakeholder outside design engineering requested a design freeze well before launch. "If we stuck to that, it would make our lives so much easier," a parts and accessories manager said (Internal company report A, 1998). By the time the product rolls off the assembly line, according to one program manger's comment, everyone is holding up "the company's victory symbol—crossed fingers" (Internal company report B, 1998). When the Company sought to improve its product development, it focused on establishing and adhering to a more methodical process for delivering the goods that customers and employees love.

In 1994 after reviewing product development literature and practices, the Company modified and codified its product development process into the Concurrent Product and Process Delivery Methodology (CPPDM) to reduce development cycle time and improve product quality. Revised four times during the last six years (with another revision underway), the CPPDM specifies five development phases, 0 (idea) through 4 (launch), and two assembly-line prototype builds of new vehicle models (the Design Intent Build and the First Production Event) in the 10 to 12 months preceding launch. (See Figure 4.1 for a summary of the CPPDM timeline.) The method's importance was reinforced when compliance became necessary the next year for the Company to obtain and maintain ISO certification. In 1997 the Company opened its Product Development Center, a new facility designed to bring design engineering staff out of headquarters, where it had been scattered among several floors, into a unified 218,000-square-foot space with sorely needed test laboratories. The new building was designed to include plenty of conference rooms for project meetings and a large central open area for displaying prototype vehicles and components.

Figure 4.1: Overview of CPPDM timeline

During the second half of the 1990s, the Company also made significant organizational changes to help product development. It established the Program Management Office (now called the Product Development Office) in 1996 to develop and disseminate excellent product development practices and to improve the product development method. In 1996 it also established matrixed lines of authority across platform and system development groups to integrate expertise particular to platforms with functional knowledge of components common to all vehicles, such as electrical systems, wheels, fuel systems, and exhaust systems. The matrix organization was intended to move gradually most design activity to the system groups, leaving platform groups to focus on integrating components and systems. In early 1998, the Company also created a purchasing group exclusively devoted to procuring developmental parts and prototypes, relieving design engineers and operations purchasing (plant personnel who manage procurement for current production) of that responsibility.

Persistence of late changes

Despite significant investments in process, facility, and organizational infrastructure, changes to designs late in the development cycle persist. Assessments of recent model years' product development air longstanding frustrations. "Late changes kill us every year," said one engineer; "Why should I believe the test, if the part is going to change?" said another, of his

dependence on another engineering group (Internal company report B, 1998). "We crated [vehicles] on launch day," one employee said, "but we uncrated them to fix mufflers and reflectors" (Internal company report C, 2000). The persistence of late changes at the Company is paradoxical in light of the CPPDM's explicit focus on combating an over-the-wall approach to development, and particularly since the method emphasizes cross-functional activities throughout the development cycle to prevent surprises requiring design alterations late in the process. The CPPDM stipulates phase-specific reviews or meetings in which people from "all affected functions" provide input to project activities and documentation. Expertise residing in multiple departments is necessary to complete these tasks, such as assessing a project's fit with strategic manufacturing goals or validating a new product's performance to specification (CPPDM, Revision 4, Phase 1, page 5). Other reviews or meetings serve to assess a project's implications for various functions or to monitor its progress. Projects satisfying the method's requirements for early cross-functional input and review nevertheless experience late changes.

Project Hook, one of the new product efforts under study, provides an example of how even straightforward and small-scope efforts might require collaboration across departments and so sheds light on how changes late in development might occur. Hook was chartered to create a new fuel pump. At the Company the fuel pump component for carbureted engines is "owned" by the system group responsible for styled surfaces, since it is part of the fuel tank, which serves as a stylistic element of vehicles and a point of differentiation among models. (An engineering group "owns" a part when it is responsible for keeping the engineering prints current and consistent with parts in use.) The fuel pump is integral to the fuel system, however, which is the responsibility of the fuel systems group. Moreover, since the fuel pump has parts visible to the user, changes must be reviewed by styling, the department responsible for the "look and feel" of

all models. Changes must also be reviewed by every platform in which the fuel pump is used. The service group, which provides replacement parts and service manuals to dealers, must know about changes to the materials and operation of the pump. Procuring components for the fuel pump requires the involvement of developmental purchasing and a supplier; validating its performance requires human and non-human resources from the test laboratory, the quality and reliability group, and road-test facilities; and integrating it into vehicles requires resources form manufacturing and assembly. Add to that the possibility that the impetus for a new fuel pump might lie outside any of the groups mentioned so far and rest instead with an engineering group focused on cost reduction—as it did in this project, managed by an employee in the value engineering department. Since the design engineer who serves as "project manager" must document that the process of the CPPDM is followed as well as ensure that the project becomes the product envisioned, he or she usually is the one to initiate the cross-functional activities informing, coordinating, and collaborating on the new product effort. If the project manager for the new fuel pump fails to engage people across organizational and disciplinary lines early in the development process, he or she may discover late in the cycle erroneous assumptions about how the fuel pump interacts with other systems, whether geometric, aesthetic, or operational. The resulting problem or problems would likely be rectified by an alteration to the fuel pump's design.

If interdepartmental interactions occur early in the development process, why are project problems and their associated changes not identified early in the process? If people with expertise are present, what characteristics of the interdepartmental reviews might prevent their identifying and solving problems?

Data collection and analyses

My data collection at the Company emerged both opportunistically and by design. Undertaken in the spirit of process consultation or clinical inquiry (Schein, 2000), it took shape in three data collection efforts, the first two of which were initiated by the field site:

- Assessing the effects of changing the timing of the two prototype builds mandated by the CPPDM;
- Identifying the strengths and weaknesses of the product development processes underlying multiple new product efforts scheduled for MY 99 launch; and
- Following one new product effort from its inception through launch.

The research that grew from these became a process of discovering grounded theory (Glaser and Strauss, 1967; Dougherty, 2001). I did not set out to study the timing and nature of cross-functional reviews but came to focus on these issues after the theme of problematic cross-department communication and numerous field site refrains of "I wish I knew these things earlier" repeatedly emerged in my notes (Bailyn, 1977).

The three data collection efforts enabled me to recognize different dimensions of product development work, as they provide complementary views of the practices of carrying an idea to functioning hardware. The Company initiates new product development with projects but launches vehicles each new model year. There is no straightforward mapping between projects and vehicles; a project may create a new model, or it may produce components to be integrated into one or many existing models. The first data collection provided a look at how interdepartmental dependencies manifested through prototype-builds. The second round of data-gathering allowed me to look at a model year's worth of work and the individual projects that comprised it. Finally, the study of a single project offered a chronologically coherent story of one product development effort at the Company. In each interview of each part of data

collection, I took notes; many but not all of the interviews were tape-recorded, depending on informants' comfort with recording, and I reviewed or transcribed the tapes afterward. At each step, my methods for data collection and analyses were closely linked. In the following paragraphs I briefly describe each of these data collection efforts and their analyses.

Prototype-build assessment

The first opportunity arose when the Company asked me to help assess impacts of moving the two method-mandated prototype builds of new vehicles closer to the annual launch date to reduce development cycle time. I spent eight days on site in the Product Development Center, Company headquarters, and one manufacturing facility and three days with Company employees in off-site meetings during January 1998. I worked with a Company employee chosen to spearhead the effort to design the data collection; together we conducted nine semi-structured interviews, and I had access to notes from 16 additional interviews that she performed when I was not on site. Departments interviewed included marketing, publications, parts and accessories, service parts, homologation and regulation, design engineering, manufacturing, assembly, and purchasing. We sought to learn how employees prepared for and executed prototype builds or used the resulting vehicles in their work; the time frame and organizational pressures under which they performed work related to prototype builds; and the anticipated consequences to their work and to their departments of staging either prototype build earlier or later in the development cycle.

To assess the impacts of changing the timing of the two prototype builds, I constructed a small dynamic model with which to simulate various timing scenarios and their effects on new product development quality at launch. The goal of simulating the model was to allow field site

representatives and me to check the internal consistency of the cause-and-effect relationships posited by informants and derived from observations of Company practices for developing, using, and "authorizing" (officially documenting and distributing drawings for) parts for new product efforts, as well as to explore hypotheses about the consequences to product quality and development cycle time. Although analysis of this model does not play a role in the findings reported here, the process of conducting the interviews and building the model highlighted different departments' responsibilities for and expectations of prototype builds. It also revealed the pivotal role that prototype builds play in focusing the organization's attention on new product efforts, as departments rely on these salient cross-functional activities to communicate a wide range of aspects of new product development projects and their effect on others' ongoing work.

Model-year assessment

The second episode of data collection and analysis took place when the Company asked me to prepare an assessment of the model year 1999 product development and launch activities with the goal of improving the development processes. I spent approximately 32 days on site in the Product Development Center, Company headquarters, and four manufacturing facilities. For the model-year assessment, I conducted 33 open-ended retrospective interviews, many of them with project teams or work groups, to obtain input from 102 individuals. Of the 10 project teams interviewed, all were scheduled to launch in the model year 1999, and three teams did not meet the launch date. During this time I also observed meetings of project teams, platform leaders, manufacturing and assembly personnel, and managers from across the Company.

During the interviews I took notes on participants' comments on 4-by-6-inch pieces of paper and placed them on the table in view of team members. This allowed them to see whether

I had correctly heard their remarks and invited differing interpretations among team members. I then used KJ diagrams (Brassard, 1989) to distill salient points from numerous qualitative data. Recording each point on a separate piece of paper allowed me to move easily into constructing a KJ diagram during the interviews, with informants helping to cluster notes into themes as interview time permitted. I then created an aggregate affinity diagram summarizing 33 interviews, by using only the cluster names from each interview as input into the aggregate diagram. This process culminated in identifying themes common across interviews of projects, departments, and facilities and left an anonymous audit trail directly to the data of each interview.

I constructed causal-loop diagrams (Sterman, 2000), using many of the cluster names as variables, to portray ways in which certain patterns (both favorable and unfavorable to product quality) might be reinforced through existing product development practices and discussed managerial policies that could weaken unproductive patterns and strengthen desirable dynamics. While the scope of the model year 1999 assessment far exceeded the focus of my emerging research on interdepartmental reviews, the themes that emerged from the KJ analysis provided a broad sense not only of the Company's current practices in new product development but also of employees' feelings about how these processes were assisting their work (or not). In reviewing the Company's product development practices for this research, I also reviewed annual assessments of launches prepared for model years 1997 and 1998 and 2000, 2001, and 2002.

Study of a single project

The third data collection effort entailed spending 10 days on site at the Product Development Center and one manufacturing facility. I initiated this data collection after my

focus on interdepartmental interactions solidified. I followed a single project, called Hook, as part of model year 2002 (launched in calendar-year 2001), through archives and interviews of individuals participating in or affected by the new product effort. For comparison, I also reviewed documentation for and interviewed project managers for five other projects. I selected project Hook because it was fairly small in scope in terms of newly engineered parts, yet it affected four platforms and more than 25 models and promised significant annual savings to the Company. It was documented thoroughly and managed responsibly and nevertheless underwent several glitches caused or identified or resolved by interdepartmental interactions. I chose to interview people who worked on project Hook individually rather than as a group; I interviewed members of styled surfaces, value engineering, developmental purchasing, and manufacturing. This allowed me to cross-check recollections of particular events during development, such as when and how a certain problem was identified.

I used data from the interviews, project documentation, and (when available) the artifacts from cross-functional reviews to construct a project timeline for events and work related to Hook, from pre-project activities to launch in the 2002 model year (attached as Appendix A to Chapter 4). Building the timeline helped restore some dimension and perspective to events that might have been collapsed by retrospective interviews. Seeking to lay out chronologically events reported by several individuals working in different departments also revealed more clearly not only that people came to know information at different times but also that they came to recognize something as "information" at different times, sometimes based on different evidence. (Even something apparently straightforward, such as when Hook was initiated, appears to depend on one's position and perspective in the organization; since so much of the

Company's work is based on projects, recognizing work as related to a project entity is important to the work being considered worthwhile and valid.)

After laying out Hook's chronology, I composed a narrative case of the project's pre-history, life, and launch (attached as Appendix B to this chapter) and reviewed and coded the case and timeline for instances of interdepartmental interaction. For these analyses I considered interdepartmental interactions to be conversations, meetings, and activities focused on new product development, and particularly on identifying problems in project work. For example, an impromptu conversation across cubicle walls discussing lab data at the Product Development Center and a thoroughly choreographed assembly of a prototype product at the plant were both recorded as "reviews." The emerging picture suggested that cross-functional project reviews were pivotal points for surfacing, synchronizing, and reinterpreting differing points of view about problems in the project and progress in resolving them. To explore this idea more specifically, I created a table (attached as Appendix C to this chapter) summarizing the information available on when each review occurred, what activity and artifacts comprised the review, the departments participating, and the project problems identified or resolved in the meetings.

Because of my increasing interest in the nature and timing of interdepartmental reviews, I used this opportunity in the field also to interview two platform leaders who take widely varying approaches to prototype builds during development, as well as several members of the Product Development Office about current and past practices for interdepartmental reviews.

Additional analysis with formal modeling

In addition to the qualitative analyses described above, I supplemented what I learned from these efforts with analysis using a formal dynamic model (e.g., Sterman, 2000). I find that simulation proves a valuable tool in understanding the complicated influences of collaboration, as it provides a method that adequately represents the interplay through time between accumulated expertise and emergent daily practices. In addition to providing a check on the internal consistency (Forrester, 1961; Sterman, 2000) of assertions of mutual causation, simulation permits exploration of a broader range of circumstances than those observed in the field. Therefore with findings from qualitative analyses, I built a model with which to explore the effects on new product development progress of the nature and timing of cross-departmental reviews. In documenting the model (documentation is attached as Appendix D to this chapter), I sought to ground each element of model structure in field data (Andersen and Richardson, 1997; Richardson and Andersen, 1995).

As with grounded theory (Glaser and Strauss, 1967), a formal model can be constructed by inferring from data some hypotheses about causal relationships that generate a particular pattern of behavior observed in the field. Model-building proceeds by representing hypotheses with connected elements of model structure, simulating the structure, comparing the simulated behavior qualitatively and in degree to the behavior observed in the field, and returning to the data to refine the hypotheses represented in the model by changing its structure. In this sense, a formal model grounded in data is a nontextual expression of a theory of the cause-and-effect relationships that systematically produce the patterns of behavior observed in the field. Through such a process of iteration, I produced a small model containing variables and interrelationships among them understandable to and considered valid by people at the field site, which also

reproduced qualitatively the patterns in new product development design changes observed at the Company. To validate the model, I showed it and a range of simulations to several staff in the Company's design engineering and manufacturing departments. These interviews with people who perform and manage the work of product development confirmed the face validity of both the causal relationships of the model structure and the simulated patterns in variables of interest.

I then used the model to explore the range of outcomes generated by varying cross-functional reviews' nature and timing. I also simulated various policies (Forrester, 1961; Sterman, 2000), or streams of decisions representing managerial approaches, for conducting interdepartmental reviews. Two of the policy simulations I discuss below in detail. The first policy was based on the CPPDM approach to interdepartmental reviews as currently implemented by Company practices. The second was derived by simulated experimentation with the nature and timing of reviews to yield the Company's desired outcome of having design changes conclude earlier in the development cycle.

Limitations of data collection and analyses

My data collection is biased toward design engineering, rather than manufacturing, in that I collected most of my data in terms of "projects" (a design engineering way of structuring work, whereas manufacturing and assembly are organized by platform); I spent more hours at the Product Development Center than in the manufacturing plants (although some of the Product Development Center time was spent observing meetings at which manufacturing and assembly representatives were participants); and I interviewed more design engineers than manufacturing and assembly personnel. I believe this bias in my data collection reflects a bias embedded in the work practices of the Company. The CPPDM, despite its stated emphasis on concurrent

development of products (by design engineering) and processes (by manufacturing and assembly), is under the auspices of the Product Development Office, which is housed in the Product Development Center and staffed largely by design engineers. The method assumes that only design engineering staff serve as project managers and discusses product development in terms of "projects." Even after the conclusion of the method's Phase 2, by which all design work is to have been completed, design engineers retain project manager status through phases 3 (equipment, tooling, and processes prepared) and 4 (launch). In my work, I sought to counter this bias toward design engineering by validating my findings, including the model structure and simulations, with manufacturing engineers, as well as with personnel from the Product Development Center.

The data I collected are also biased retrospectively, in that many of the interviews focused on activities and projects nearly or recently completed. The primary danger in retrospect is that it is often hard to remember what was *un*known at a particular time; hence there is a tendency to overlook *how* something was made apparent or to forget the assumptions that guided particular decisions. The benefit of retrospect, however, is that it can offer perspective to events and patterns unfolding during processes stretched out through time and over many people playing various roles. I believe the three distinct approaches to collecting data on product development activities at the Company provide sufficient variety of data to counter and complement the retrospective bias.

Perhaps the most significant limitation of the data collection is that it draws from the experiences of only one organization and so may not provide sufficient variety to support generalization to other organizations. Based on my readings of the literature and experiences in this and other organizations, I surmise that the Company's practices are neither the best nor

worst in most aspects of product development. The focus on developing grounded theory of the *processes* at work during interdepartmental interactions, however, might be generalizable (Dougherty, 2001), even if the specific practices manifesting those processes at the Company are not. Moreover, constructing a model from the field site data allows simulated exploration of mechanisms of cross-functional interaction using circumstances and scenarios broader than those observed during data collection. In this way the modeling and simulation presented here provide a bridge from the specifics of the single site studied to propositions testable in other settings.

4.3 Findings from qualitative analyses

From qualitative analyses of the prototype-build assessment, the model-year assessment, and the single-project study described above, several findings emerged regarding the knowledge related to product development distributed throughout the Company and the activities that elicit it and bring it to bear on new product efforts. In the paragraphs below, I describe these findings and some of the data supporting them. In the next section (4.4), I use inferences about interdepartmental interactions to develop a simple model to explore expertise stimulated and exercised across the design-manufacturing boundary. Briefly, the three findings from qualitative analysis follow.

- The distribution of expertise throughout the organization is acknowledged by employees but not necessarily understood. While individuals recognize that knowledge for doing various aspects of work almost certainly exists within the organization, it is not clear where, or with whom, specific types of expertise reside.

- Interdepartmental reviews of new product projects-in-process provide occasions for identifying and developing expertise distributed in the organization and opportunities to identify problems and pose solutions in the new product under review. I observed three basic types of interdepartmental reviews of new product efforts at the Company: the

project review, the mock-up or model-year review, and the prototype build. The three types of reviews are designed to complement one another by gradually shifting product development attention from design to manufacturing as the development cycle progresses.

- A mismatch can occur between aspects of a review and the customary practices of participants in the review. When the locations, artifacts, and actions of a review are congruent with participants' familiar ways of knowing and doing work, they can contribute what they know about the work and thereby learn more from review activities. Incongruence between participants' practices and a review's attributes effectively suppresses, rather than solicits, involvement and expertise relevant to the work at hand.

Distributed expertise

Even though individuals in the Company realize that "someone else knows this," they do not necessarily know *who* knows, or how to find out who knows. An example of this comes from Max, in the Product Development Center's value engineering group, project leader for Hook. Previously Max had worked in the parts and accessories division in the downtown headquarters, which did not use the CPPDM. Upon moving to the new product facility and taking responsibility for Hook, Max needed to learn to navigate through a new work process and the organizational set-up of matrixed platform and vehicle system groups, as well as become familiar with new individuals and the expertise they possessed relevant to his project. He said,

> [I]t was a problem with not only asking the questions and getting people to answer the questions, but even finding who the right people to ask the question *to* was difficult.... In some cases it was really just, you know, essentially just tracking them down. And you ask a person, and they're the wrong person to ask, but they direct you to the next person, and you ask that person. And maybe they're the correct person, or they direct you to the next person (interview notes, MZ1.4).

Other examples of confusion about where expertise resides come from employees expressing frustration with what they call "tribal knowledge," which connotes that expertise exists in isolated pockets of the organization. The often-repeated phrase also suggests that

access to that knowledge is conferred by induction into specific social practices, the nature of which outsiders or newcomers may be unaware and unable to initiate. Employees with long tenure expressed uncertainty about where in the Company certain kinds of expertise lay, perhaps because the Company's growth exceeded rates of orientation and social assimilation, or perhaps because processes and roles, whether newly designed or evolving as undesigned, were insufficiently defined. "Ask who should be at a project review, and everybody tells you a different answer," said one design engineer. A manufacturing engineer said, "Every time I talked to someone, it [the direction on how to proceed] changed—then I was told about decisions that didn't consider what our processes can support." These remarks suggest that expertise needed for product development is distributed and not easily identified or obtained by the person needing it. They also indicate that the distribution of expertise in the organization continually shifts through time, as personnel, organizational, and procedural changes alter work and social paths that surface and confirm who knows what.

Occasions of identifying and developing distributed expertise

In this unmapped, unstable terrain of organizational expertise, interdepartmental reviews and meetings play a critical role in identifying as well as stimulating and developing the know-how distributed in the Company. Others' expertise can prove crucial to recognizing, naming (Preston, 1991; Suchman, 1995), and resolving problems in a new product design or in its implications for other departments' work. (A design affects others' work adversely if, for example, although it meets technical performance specifications, it cannot be produced rapidly enough in the current assembly plant to meet production goals, or if it renders popular and highly profitable accessory components incompatible.) Reviews develop individuals' knowledge of the

new product as it relates to their work. By seeing and interacting with the product under development during reviews, participants build their understanding of how to design, manufacture, service, and market the new good, and so be competent in their work. At the field site, I observed three main types of reviews in which multiple departments participated: the project review; the mock-up or model-year review; and the prototype build. Each type is seemingly initiated by and receives impetus from a different part of the organization. In keeping with the framework proposed in Chapter 3, I briefly describe below characteristics of these three types of review (also summarized in Table 4.1) and discuss ways in which each influences knowledge about new product work.

Project reviews

A project review is almost always instigated by the project manager of a new product development effort. Usually the purpose of the review is to present and assess technical aspects of a single project's parts or component design.

Location. Project reviews usually take place for one to two hours in a Product Development Center conference room (most convenient for design engineers),

Actions. Project reviews often entail the project manager's making a prepared but informal presentation. Primary actions include talking (by the project leader), listening (by review participants), and discussion (by all) of questions and issues that arise during the presentation.

Artifacts. Artifacts used include paper on which the meeting agenda and/or project summary are written; PowerPoint slides displaying words and perhaps two- or three-dimensional

Table 4.1: Three types of reviews

Type of review	Unit of focus	Instigator	Partici-pants	Artifacts	Actions	Locations	Timing	Participa-tion	Accessi-bility	Example of problem identified
Project review	Project	Project manager (design engineer)	Design engineering Develop-mental purchasing Reliability, Service, and other staff groups as invited	Overheads or slides Two- or three-dimension-al sketches	Presenta-tion by project manager Informal discussion	Product Develop-ment Center conference rooms	At discretion of project manager; at least one or two during Phase 1, possibly more if large scope	Design engineering —active Others —passive	Design engineering —high Develop-mental purchasing —medium to high Others— low to medium	Drawing specifying filter mesh size differs from mesh size currently in use
Mock-up / Model-year review	Platform / Project	Product Develop-ment Office (staffed primarily by design engineers)	Design engineering Develop-mental purchasing Reliability Homologa-tion Service Marketing Parts and Accessories Manufac-turing engineering	Overheads or slides Projected CAD images Prototype parts or vehicles (occasion-ally)	Presenta-tion by platform leader and/or project managers Question-and-answer session	Product Develop-ment Center open area	Calendar-driven; mock-up— nearly monthly model-year— three times a year	Design engineering —active Others— usually passive	Design engineering —high Develop-mental purchasing —medium to high Others— low to medium	Changes in frame jeopardize compatibility of popular after-market accessory

Table 4.1 continued: Three types of reviews

Type of review	Unit of focus	Instigator	Partici-pants	Artifacts	Actions	Locations	Timing	Participa-tion	Accessi-bility	Example of problem identified
Proto-type build	Platform / Model	Product Develop-ment Office (method-mandated) or Platform leader (both usually design engineer)	Manufac-turing engineering Assembly Design engineering	Prototype parts and vehicles	Fabricating parts and assembling compo-nents and vehicles	Manufac-turing plant (on or off assembly line)	Method-mandated: calendar-driven, 11 and 6 months before launch; Platform-instigated: at discretion of platform leader	Manufac-turing engineering —active Assembly—active Design engineering —usually passive	Manufac-turing engineering —high Assembly —high; Design engineering —medium to high	New frame design prevents mounting the engine with existing tooling infrastructure

sketches of parts and/or graphs showing data from test results; and occasionally product prototypes ranging from eighth- or quarter-scale plastic models to full-size hardware models. After the review, the project leader at his or her discretion may prepare and circulate minutes from the meeting. He or she often files copies of the presentation in the project book documenting each phase of the project's development, which is seldom referred to by others.

Timing. Since project reviews take place at the discretion of the project manager, their frequency and timing vary extensively, depending on the new product's scope and duration and on the project manager's style. The CPPDM requires "technical design reviews" during each of phases 1 and 2 of development, however, so a project will have a minimum of two and perhaps as many as a dozen project reviews, usually relatively early in development.

Participants in project reviews most often include design engineers and developmental purchasing staff from interdependent projects or vehicle systems. Depending on the nature of the project and the invitation of the project manager, project reviews may also include representatives from departments (perhaps housed at other facilities), such as reliability (which assists with DFMEAs and PFMEAs), homologation (responsible for ensuring vehicles meet the emission requirements of each market), service, marketing, parts and accessories, and, less commonly, manufacturing and assembly, whose members are likely to participate by telephone rather than appear in person.

Because most participants are design engineers, the review content tends to focus on design issues, even when representatives of other departments are present—which in turn tends to reinforce dominant participation by design engineers and not others. Additionally, as mentioned above, project review artifacts often include two- or three-dimensional sketches and drawings (produced manually or in CAD, or Computer-Aided Design machines), as is often

appropriate to work early in the development cycle. Although nearly anyone, by invitation or request, could attend a project review, they are accessible, in the sense used in Chapter 3, primarily to people familiar with the tools and activities of design engineering. In other words, these reviews give people already skilled in practices of design the ability and inclination to know and interact with the design under discussion.

While the sketches and slides used in project reviews are useful in representing the state of a new product and in raising issues relevant to design, they do not necessarily help participants raise alternative designs. For example, a service technician attending a project review for Hook asked if the new fuel pump would eliminate an intermittent problem of siphoning that plagued the current component. The project manager said that the supplier had proposed a vent near the top of a fuel filter to reduce the likelihood (see Appendix B to Chapter 4 for elaboration). No alternative design was explored, either during the review or afterward, until questions about the solution's efficacy emerged later in development. Neither do design-oriented reviews help participants spot potential problems in tolerances among parts or other manufacturing issues, or possible problems with accessibility and tool adequacy for later service and maintenance of the product components. For example, the fact that the new fuel pump used metric bolts, although the assemblers handling it were equipped with English wrenches, was not discovered until assembly at the plant was attempted during a prototype build. Thus project reviews largely elicit and stimulate knowledge of design issues of the new product and "conscript" (Henderson, 1991, 1998) others to accept and appreciate the proposed design.

Mock-up and model-year reviews

Mock-up and model-year reviews are driven by the Product Development Office and are not concurrent practices; the office first established mock-up reviews in 1998 and then gravitated to model-year reviews by mid-2000. Model-year reviews and mock-up reviews are two approaches to accomplishing the same goal, disseminating information across projects and departments to surface integration issues, and so I describe them as a single type of review. These reviews are organized and executed by model year under development and by vehicle platform, not project, because they seek to instigate conversation about integration of new product development efforts. Even so, many presentations and much of the discussion focus on individual new product development projects, reflecting design engineering's unit of work, in contrast to the work of most of the audience, which is organized by platform or vehicle rather than project. Participants include not only design engineers from platform and vehicle system groups and staff from groups in the Product Development Center such as developmental purchasing, reliability, and homologation, but also significant representation from departments housed in other (local) facilities, such as service, marketing, and parts and accessories. Mock-up and model-year reviews also draw low-to-moderate representation from manufacturing plants, most of which are located in other cities.

Location. Mock-up and model-year reviews take place in the central open area of the Product Development Center.

Actions. The reviews are intended to convey, within a short time, large amounts of information from design engineering to "representatives of all affected functions," (CPPDM, Revision 4, Phase 1, page 5) about multiple model years' efforts and usually consist of back-to-back presentations that consume most of a day. Participants assembled for mock-up and model-

year reviews often comprise a large group, and review actions take the form of formal presentations by platform leaders or project managers, with the audience speaking primarily during question-and-answer sessions.

Artifacts. Artifacts often include PowerPoint slides displaying words, two-dimensional drawings of parts and components and projection of three-dimensional CAD drawings that are then rotated as the presenter describes various aspects of the design. Occasionally full-scale hardware prototypes of parts and components, perhaps displayed on a prototype vehicle, are also present and referred to during presentations. When mock-up reviews were held, the Product Development Office expressed the expectation that each new product development project would place up-to-date prototype parts on vehicles permanently displayed in the open area of the Product Development Center. Coincident to the ascendancy of model-year reviews, the vice-president of engineering began to call for a wider use of virtual artifacts made possible by projecting CAD drawings. Documentation of these reviews varies. In the case of mock-up reviews, the Product Development Office published a compilation of the new product development presentations (by project), their unresolved issues, and next-step summaries. In the case of model-year reviews, presenters are asked to place their presentation slides on a commonly accessed server, but compliance is sporadic.

Timing. While mock-up reviews took place nearly monthly, model-year reviews take place three times a year, roughly in October, January, and April (with the annual launch taking place in summer). The calendar-driven timing means that new product efforts appear in a wide range of readiness, depending on when the review occurs.

Mock-up reviews were made up of more, but briefer, presentations covering smaller scope; more often included references to prototype vehicles; and drew smaller, more focused

audiences, so the question-and-answer sessions occasionally grew lively. Model-year reviews' increasing use of virtual artifacts may play a role in reducing participation by non-design engineers, as the display of engineering configurations conveys new product information in forms in which some do not have the capability of working. Only engineers at the Product Development Center have ready access to CAD; there are few machines at each plant, and one design engineer acknowledged that manufacturing "does not work off the ProE models yet...and may not have the processes to do so" (Interview notes, SM.2.3). During my observations of mock-up and model-year reviews, I heard people remark in undertones during or after presentations that participants (audience members) were "too quiet" or restrained in raising questions. More pointedly Karla, a member of the Product Development Office, said that some design engineers who present regularly are growing disenchanted with model-year reviews. "They [the presenters] say, 'We're looking out at a sea of glazed-over eyes,'" Karla said, "like they're standing up there talking and nobody is getting anything out of it" (Interview notes, KL.1.2). Bob, a manufacturing engineer, reasons that the audience is made of up of "realists."

> People who think they're realists here mean, "I only deal with hardware. I don't deal with theory." That's typical manufacturing—you can show somebody a drawing or a model or a model in 3-D and they'll say, "That's great. When I see it in my hand, I'll believe it" (Interview notes, BL.3.2).

Cary, a parts and accessories engineer, admits, "We rely on builds more than drawings" (Interview notes, CR.1.2).

Non-design engineers, then, as the receivers of information and perhaps skeptical of "theoretical" models, tend to play a passive role, except during question-and-answer sessions following the presentations. Parts and accessories and service departments learn, for example, that a brake project has been postponed, a flywheel improvement is experiencing durability

issues, a new cosmetic project is to be launched sooner than had been planned. That knowledge is, however, structured by design engineers, and it tends to center on general awareness of new product efforts rather than on specifics of how to manufacture or service them. Upon hearing one announcement of an early introduction, a service technician stood up and said it was exciting but he was "terrified" about the resulting tight schedule for training technicians to service the new product.

There are two additional challenges to non-design engineers' increasing their knowledge of the new product. First, the non-design engineer must spontaneously articulate an issue in the relatively unstructured arena of the question-and-answer session (compared to the prepared presentation of the design engineer). Second, the artifacts prepared by the design engineer may not adequately represent (in number of dimensions, measurements, etc.) information that the non-design engineer regards as relevant and important in expressing his or her concern to others. Thus a valid point by a manufacturing engineer may remain un-voiced or, once articulated, may be regarded as invalid by the design engineer leading the session and so given little time or credence for further consideration. For example, I heard a design engineer in the audience of a mock-up review privately comment on a service parts engineer's objection to a part change, saying that "Ben likes to make trouble." Perhaps Ben indeed makes trouble; even so, the possibility that he raised a valid concern appeared to be dismissed.

Prototype builds

The third type of cross-departmental review of new product development work consists of "builds," assemblies of full vehicles from prototype parts. The CPPDM mandates two builds in every model-year development cycle. Their existence actually precedes the publication of the

CPPDM, and because these two builds have taken place annually for years, the entire organization is entrained to them and regards them not just as a given part of product development but as necessities for subsequent launch. Both design and manufacturing divisions are keenly aware of these builds, their cut-off dates for securing prototype or production parts, and the importance of appearing prepared and competent when they occur. The method-driven builds are defined in the CPPDM as follow:

> Design Intent Build (DIB): For a project to remain in the model year specification "X"[1] months prior to launch, the components and assemblies representative of the final design (design intent) must be available for assembly...at the assembly plants.... Components may be either prototype or from production tools and processes. Concurrent with design intent [build], vehicle assembly parts and BOMs [Bills of Materials] ...are to be submitted for authorization....
>
> First Production Event (FPE): For a project to remain in the model year specification, FPE vehicles must be built at least "X" [1] months prior to launch.... The First Production Event vehicle is to be built from 100 percent production tooled components and processes (CPPDM, Revision 4, Definitions, page 3).

Over several days the DIB usually produces 15 to 30 vehicles for each platform, and the FPE usually produces three times that amount. (Standard production volumes are about 200 vehicles per day per assembly line.) Design engineers responsible for new product efforts are always present at the plants for the DIB and sometimes present for the FPE, although on the production line all assembly is performed by plant personnel. Builds conclude with debriefing meetings among assemblers, manufacturing engineers, and design engineers.

The other prototype builds that occur are platform-instigated, as they take place at the discretion of the platform leader (not a project manager), a design engineer who ensures that all

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[1] Where "X" is specified each model year by the Product Development Office.

new product development efforts affecting models within a vehicle platform integrate smoothly with each other and with existing model configurations. Platform-driven builds occur rarely if at all, and when they do it is usually early in the development cycle, well before the DIB.

Location. As the excerpts from the CPPDM indicate, the DIB and FPE take place on the assembly lines and the manufacturing plants. Usually representatives of manufacturing engineering and assembly are present and participate with laboratory staff or design engineers in assembling the vehicles. (Union rules govern who may assemble a vehicle, depending on the location and intent of the activity.) Platform-driven builds may take place at the Product Development Center, where they focus on assembling a single vehicle, or at the plant, where they center on assembling two to 40 vehicles off the assembly line. Builds at the Product Development Center usually have present at most a few representatives from the plant, while platform-instigated builds at the plant involve a broader base of plant personnel.

Actions. Because the primary activity is to assemble vehicles using newly developed parts, the focus is clearly on the platform and its models, in keeping with the focus of plant personnel's work, and there is little project-oriented discussion.

Artifacts. Clearly the salient artifacts for both platform-driven and method-mandated builds are the prototyped components and the assembled vehicles. Additionally, before builds, manufacturing and assembly may prepare fabrication and assembly process "walk-throughs," or procedure outlines, documenting them on paper. Although documentation of platform-instigated builds varies widely, during the DIB and FPE, it is customary that easels with large pads of paper and markers stand near each assembly line so that any one may immediately record concerns identified during the prototype build. While service, marketing, and personnel from other departments usually do not participate in creating hardware prototypes, they often have access to

the vehicles that result from the DIB and FPE builds and use them for reviewing and testing their work related to the new product development efforts.

Timing. The timing of the method-driven prototype builds is the most consistent of any of the reviews and occurs fairly late in the development cycle. Each platform holds its DIB eight to 11 months before launch and its FPE four to six months before launch. Because platform-driven builds take place at the initiation of the platform leader, they depend on manufacturing and design engineering management's willingness to support the effort, and their timing varies extensively. As mentioned earlier, however, they usually occur early in development, well before the DIB, if they occur at all.

The method- and platform-driven prototype builds actively involve manufacturing and assembly personnel, as well as design engineering, with tangible specifics of the new product under development. Assembling prototype hardware into full vehicle configurations includes many actions that elicit knowledge of current and possible tooling and process capabilities and provides a fresh look at the outcome-to-date of the design work performed. Prototype build reviews typically reveal the design's implications for assembly and manufacturing. Some of these are addressed by changes to the manufacturing process. Issues identified at builds are often addressed through design changes, however, although they may have remained unidentified through several iterations of design reviews.

Because of their salience and highly interactive nature, prototype builds intensively engage and often significantly increase manufacturing and assembly and design knowledge of new product development issues. At later stages of development, prototype builds themselves may not necessarily stimulate design engineering knowledge of new product design, although preparing for builds guarantees design engineers have learned enough to obtain prototype parts

from fabrication in manufacturing or from suppliers. Prototype vehicles emerging from these reviews also develop new product knowledge in service, marketing, and other departments to the extent that they have access to and use the vehicles to review and test their own work related to the new product efforts. Parts and accessories engineers assess fit of after-market accessories with original equipment; service engineers test newly developed tools to ease replacement of wearable parts on the new-model-year vehicles; and marketing staff prepare photography sessions for brochures and catalogs.

A mismatch between review activities and participant expertise

The preceding section suggests that, of the three types of reviews described, prototype builds most directly elicit and develop knowledge about new product design and manufacturing. They create awareness of others' expertise across the design-manufacturing boundary, and the resulting artifacts (vehicles) boost other departments' knowledge of new products and specific implications for their work. When viewed in light of the framework proposed in Chapter 3, prototype builds provide the review most accessible to manufacturing and assembly, developing and deepening plant personnel's ability and inclination to understand the new product and its impact on their work. Reviews that use functioning hardware in the production setting thus elicit high involvement from manufacturing and assembly and enable identification of problems previously unrecognized or unresolved and subsequently well addressed through design changes.

On the other hand, my observations of project and model-year / mock-up reviews suggest there is a mismatch between the skills of the participants invited and the artifacts used during the review. As mentioned by those speaking of CAD images used during reviews, people outside design engineering may not participate vocally because the work as represented is not accessible

to them; they cannot relate to it using the tools and activities with which they usually do their work. Rather, they rely on builds to learn what they need to know about the new product, because, as Bob in manufacturing says, "Everybody speaks hardware" (Interview notes, BL.3.2). While focusing on design issues with design-savvy audiences can be appropriate to project reviews early in development, if early reviews are expected to surface and solve a new product's latent problems, then identifying problems may require a view of the product other than line representations of its design or words describing its intended features.

Effects of the mismatch in the flow of work

In many respects the three types of reviews are complementary, with project reviews focused on component technical design, mock-up/model-year reviews centered on integration of projects into platforms, and prototype builds providing a coherent picture of the new products at the vehicle level. All three types of reviews stimulate problem identification, which then frequently leads to design changes. It is the method's intent that early technical reviews and periodic model-year or mock-up reviews surface primary design changes, so that by the time method-driven prototype builds occur, the focus can shift to tooling and process preparation. Ideally, reviews early in the development cycle would surface and solve latent problems in the product under development, so that by the time the Design-Intent Build occurs, it is indeed representative of the product's completed design.

The silence of non-design participants during earlier reviews, however, and the surge of changes coinciding with prototype builds both suggest that only interdepartmental interactions using actions, artifacts, and locations familiar to non-design engineering participants in their daily work significantly increase their knowledge of the new product. Once non-design

engineers gain an understanding of the new product, they generate ideas and suggestions for altering it, so that producing it does not jeopardize their own departments' cost and quantity targets for manufacturing, service, or other functions. Thus the mismatch between participants' skills and the dimensions of early reviews is problematic because the Company expects reviews to identify problems in new product work early in the development cycle.

At the Company prototype builds frequently elicit design changes. Matt, a platform leader coordinating development efforts to create a new model with significant changes to both powertrain and chassis, offers an example. Breaking with common practices, he planned a number of prototype builds at the plant, off-the-line, early in the development process. He said he wished the project team had built at least one prototype vehicle at the Product Development Center even before going to the plant for its first early build, 18 months before the scheduled DIB, because that first hardware assembly effort identified a major problem.

> On CAD, the engine fits into the frame. And once it's there, it does fit. The problem is getting it in there. There wasn't a big enough hole in the frame to bring it up from the bottom. It's like the ball in the box. It fits once it's in there, but you can't get it in there. So we had a ship-in-the-bottle problem (Interview notes, MM1.2.1).

Method-driven prototype builds, whose stated purposes are to mark the end of design and to try out new manufacturing processes, also stimulate changes. When design changes arise from the DIB and FPE, they occur at a point in the development cycle when the Company seeks product stability to prepare tooling and processes without incurring costly changes to accommodate different design geometries or interfaces. Figure 4.2 shows a graph of problems logged in new product efforts during the weeks before launch in model year 2000 (Internal company report B). The basic two-humped phenomenon is not unique on that particular model year; it essentially repeats each year (although the magnitude of the problem-surges varies), indicating that the

method-driven prototype builds trigger changes, since many problems identified are then resolved through alterations to design.

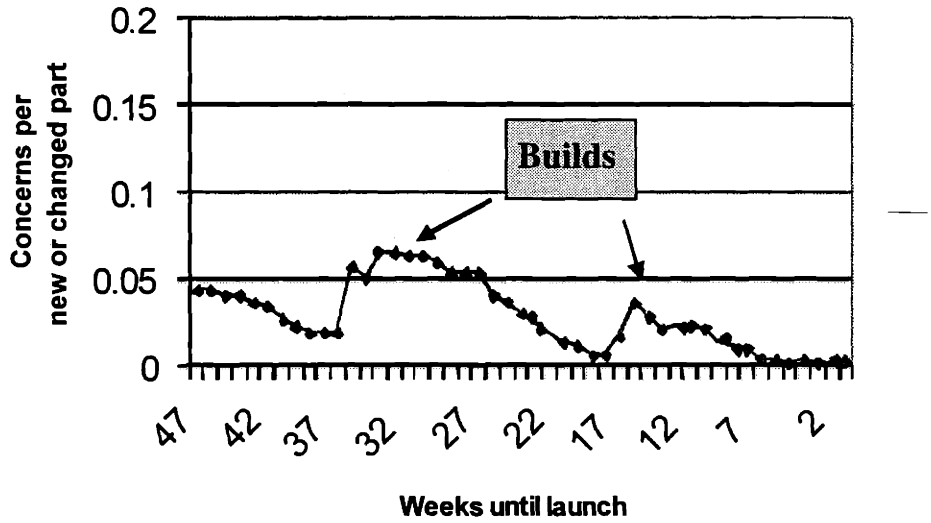

Figure 4.2: Concerns per new or changed part in model year 2000

Paradoxically, then, the review that the CPPDM says should signal the end of design, the DIB, stimulates changes to the new product design. It may be that the Company's prescribed method for engaging in interdepartmental reviews—with virtual or design-tool-centered early reviews and hardware-focused later reviews—can activate, rather than eliminate, changes to design late in the development cycle. "Late changes" may result from people following the CPPDM's activities for each phase, adhering to the recommended sequence and staging them in accordance with expectations in the design engineering department for what makes a "good" review.

The mismatch between a review's artifacts, actions, and location and its participants' usual practices is further exacerbated by design engineering's focus on projects, while manufacturing and assembly organize work by platform, and by the ways that each department views "reasonable" use of scarce resources. Given that early interdepartmental reviews examine

projects whose design is incomplete, design staff regard it as expedient and useful to focus on design issues using design language, and non-design staff are content to let design engineers work out details until they can provide "assurance that the design is good," says Ted, a manufacturing engineer, which is signaled by committing the design to prototype hardware (Interview notes, TB.4.7). The catch is this: To prove effective, a new product design must be informed by knowledge of non-design engineers, who cannot "know" the new product until they experience it using tools and actions customary to their work.

4.4 Modeling interdepartmental interactions in new product development

Why modeling can prove useful

The previous section's comparison of three types of reviews revealed that interdepartmental review activities, as embodied in their artifacts, actions, and locations, play a role in soliciting or suppressing expertise in different parts of the organization related to developing new products. Each type of review, however, was observed to occur with different frequencies and at different points in the development cycle. While the qualitative comparisons among locations, activities, and actions of the three types of reviews suggest how dimensions of joint activities shape participation by different people within a particular review, it is harder to draw conclusions about effects of different review timing on distributed knowledge and its role in project progress. Each type of review is not necessarily repeated throughout the duration of the development cycle; rather, project reviews at the Product Development Center usually take

place early in development, and prototype builds at the plant usually take place late in development. Moreover, the dimensions of joint activities—artifacts, actions, locations, and timing—are intertwined. The artifacts most easily produced early in development are engineering drawings, not prototyped hardware. The nature of drawings constrains the actions that can be undertaken with them, as well as what is considered a "reasonable" location for engaging in conversation over sketches; there may be little benefit in going to the assembly line, rather than the engineering office, to look at them.

During a development cycle the three types of reviews display a range of accessibility to manufacturing and assembly. Prototype builds on the assembly line actively engage plant personnel, while many model-year and mock-up reviews promote more passive participation. Active participation by manufacturing and assembly is important because it plays a role in identifying latent problems, which are often resolved through alterations to design. In considering how to identify and resolve latent problems earlier in the development cycle, it must be acknowledged that not all elements of the reviews most accessible to manufacturing and assembly may be available at all times during development. But given that interdepartmental reviews are occasions of structuring organizational expertise, how does timing of those reviews affect distributed knowledge of new product development and the progress of work?

To explicate the effects of timing of cross-boundary activities (as distinct from artifacts, actions, and locations) on distributed expertise and progress in interdependent work, I use simulation, since it permits experimentation with observed relationships between participants' accumulations of knowledge and activities under circumstances and conditions not necessarily found in the field. In modeling I emphasize assessing whether reviews accessible to manufacturing and assembly (assumed, for the moment, to be possible), under different timing,

produce the "ideal" pattern in development progress. If so, then one can explore how to bring about reviews accessible to all parties at various points in development. In other words, the purpose is not only to simulate what is observed and possible, but also to simulate what has not yet been observed, which may not be possible or is currently possible only at considerable cost. By using the simulated world to learn more about interactions between the timing of joint activities and participants' accumulations of knowledge relevant to new product work, we can then take that understanding to the real world and reconsider what is relevant to and possible in the context at hand.

Model overview

With this model I build on what was learned in the previous section to explore effects of timing of interdepartmental reviews that are more and less accessible to manufacturing. The model consists of three sectors, or views, shown in Figure 4.4 : knowledge about the new product under development; the interdepartmental review; and new product development work.

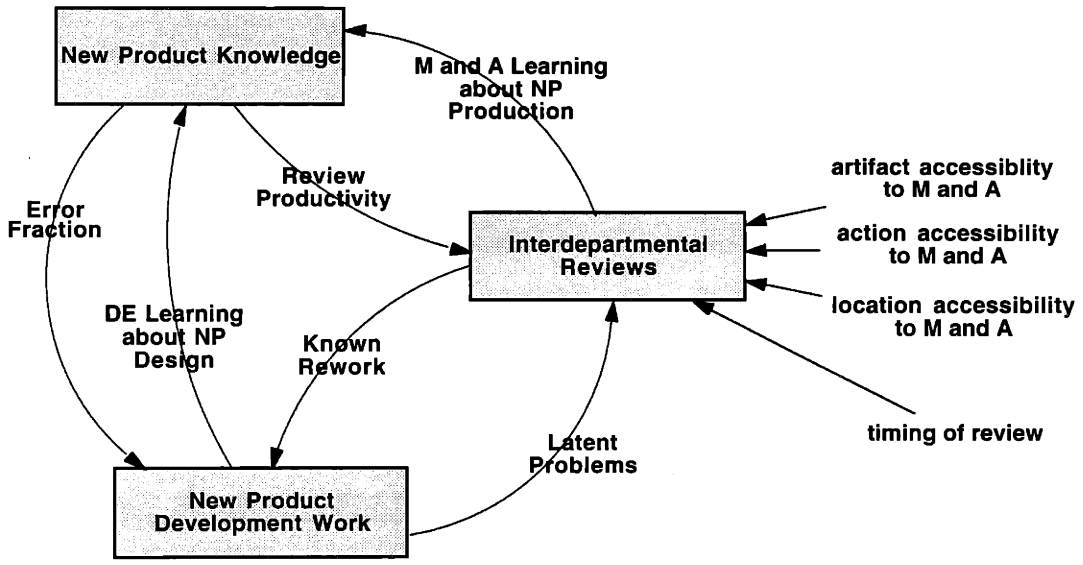

Figure 4.4: Model overview

As design engineers make progress in new product work, they stage interdepartmental reviews using artifacts, actions, and locations (dimensions of review accessibility) that convey the current state of the product design. From these reviews manufacturing and assembly personnel learn about the new product (new knowledge) and its production challenges and help identify problems (rework) that are often resolved through alterations to the product design. As design engineers address problems and learn more about the new product design, the probability of error (error fraction) in subsequent work decreases.

As a reference mode (Sterman, 2000), or observed pattern of interest to simulate, I use a stylized pattern (see "Current" in Figure 4.5) of open concerns per new or changed parts (shown as Figure 4.3 in the previous section). I take "open concerns per new or changed part" as a proxy for problems identified in new product work addressed through design changes. I also infer an "Ideal" reference mode (also shown in Figure 4.5) from the Concurrent Product and Process Delivery Methodology's definition of the Design Intent Build as signaling the end of design, as well as from interviews in which people asserted that design activity should conclude by the time the DIB occurs.

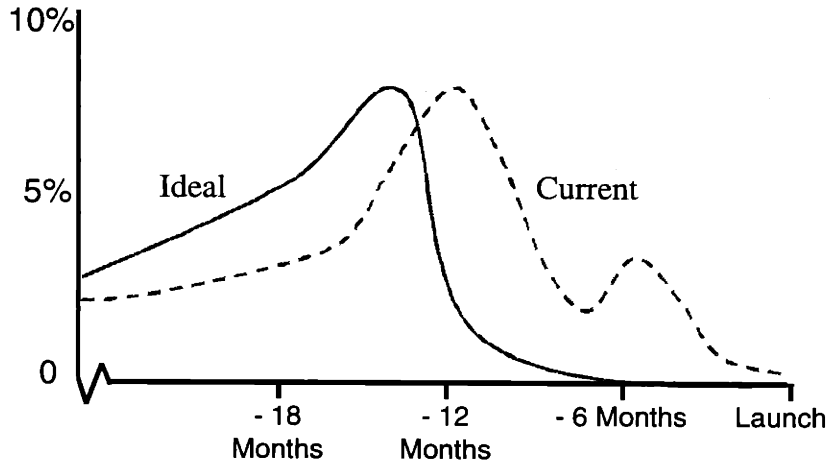

Figure 4.5: Current and Ideal reference modes for problems identified per new product task

While there are multiple departments involved in new product development—marketing, design engineering, service, laboratory testing, developmental and operations purchasing, styling, manufacturing, and assembly, to offer a partial list—for the purposes of the model, I focus on just two, design engineering (DE) and manufacturing and assembly (M and A). These departments are far from each other in terms of social distance; their educational backgrounds, career aspirations, and work environments differ. At the Company, their work locations are far apart geographically. Design engineering and manufacturing and assembly are also far from each other in terms of the project timeline, as design engineering is responsible for the idea generation and project initiation, and manufacturing and assembly bear responsibility for producing the tangible goods for public consumption. I reason that if we can understand the dynamics of collaborative work between these two extremes, then we can effectively understand the processes of interdepartmental interactions among these groups and intermediate departments.

For the model I adapt the framework for interdepartmental interactions proposed in Chapter 3 to the Company data by focusing on a review's accessibility to manufacturing and assembly (see Figure 4.6a). In contrast to Chapter 2's model of doctor-technician interactions, where aspects of the cross-boundary interaction were highly constrained with respect to location, timing, artifacts, and actions, in the case of interdepartmental reviews at the Company, all of these attributes of interaction result from choices made by someone, often design engineers serving as project managers or working in the Product Development Office. At the Company, design engineers or the Product Development Office (which is housed in the Product Development Center and staffed primarily by design engineers) initiate, structure, and lead virtually all project reviews, mock-up/model-year reviews, and prototype builds, and the

customary location for reviews, except for the method-mandated builds, is the Product Development Center. For these reasons I assume that review artifacts, actions, and locations are within the customary practices of design engineering, and the issue is whether reviews are or can become accessible to manufacturing and assembly personnel, whose practices, tools, and focus differ markedly from design's.

Although in reality locations, actions, artifacts, and timing are intertwined, in the model I represent them as independent to understand better the effects of differentially accessible reviews under different timing scenarios on project progress. I further adapt the theoretical framework to simulated exploration by making variables of manufacturing and assembly participation and review accessibility to manufacturing and assembly, rather than leaving these dynamics implicit in the feedback between accumulations of knowledge and activities. As was described in Section 4.3, at the Company manufacturing and assembly personnel often are present at reviews—they "participate" in the broadest sense of the term—even when the reviews are not accessible to them because the artifacts, actions, and location differ significantly from their usual ways of knowing and doing work. Thus the model deconstructs the theoretical framework's recursive cycle of participation by and accessibility to manufacturing and assembly (as in Figure 4.6a) to make "levers" of M and A Effort to Participate, Location Accessibility to M and A, Artifact Accessibility to M and A, and Action Accessibility to M and A (see Figure 4.6b), which affect how manufacturing and assembly staff gain knowledge about the new product. The timing of the review also becomes a lever for simulated exploration. (Below I discuss in more detail the model conceptualization for interdepartmental reviews and their timing.)

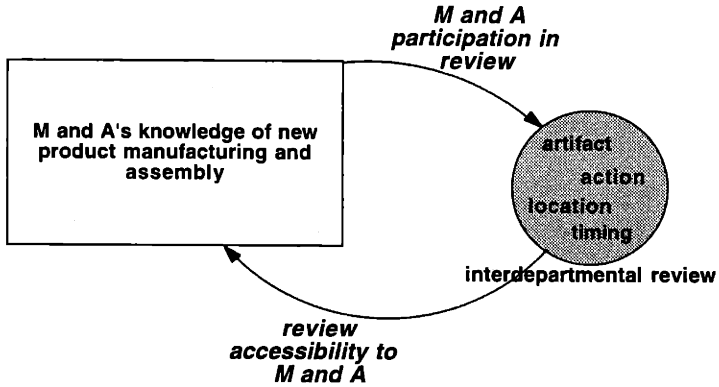

Figure 4.6a: Focusing on participation of and accessibility to Manufacturing and Assembly

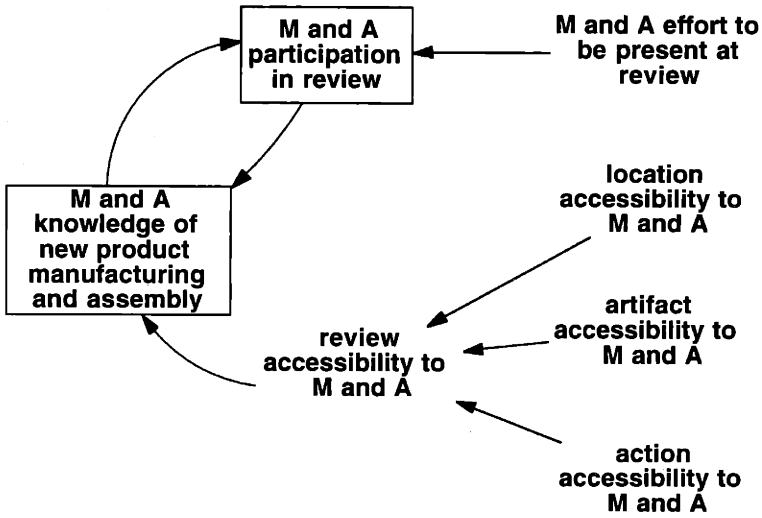

Figure 4.6b: Representing dimensions of reviews as levers

In this model I simplify greatly the reality of multiple projects integrated with each other and with existing product configurations to form new-model-year products, to focus on the nature and timing of reviews and their impact on new product development progress. Since others have explored issues of integrating interdependent tasks (e.g., Cooper, 1980; Ford and Sterman, 1998), I focus instead on independent tasks, each of which depends on integrating knowledge from both design and manufacturing. This model therefore represents one model year's work as comprised of "tasks" related to a single launch that need work by design

engineers and review by manufacturing and assembly to ensure accuracy. I choose as the time horizon 24 months, which is the time frame in which many of the Company's projects (except for those of very large or very small scope) are expected to launch.

Knowledge about new product development

Ample literature (e.g., Polanyi, 1966; Henderson, 1991; Nonaka, 1994; Carlile, 1997) as well as empirical observation suggests that different departments specialize in different kinds of knowledge. Here I represent two distinct accumulations (also called "stocks") of knowledge, Design Engineering Knowledge of new Product Design and Manufacturing and Assembly Knowledge of New Product Manufacturing (see Figure 4.7). It is not necessary to assume that every individual in each department possesses the same knowledge, only that most of the organization's knowledge about the new product's design resides in the design engineering department, and most of the knowledge about how to mass-produce the new product forms in the manufacturing and assembly staff. We could consider, too, that design engineers may accumulate expertise in manufacturing through years of work or through a cross-functional residency program and that over time manufacturing staff might in similar ways learn significantly about new product design. But these cross-disciplinary stocks of knowledge would accumulate over a longer time horizon than the 24-month time frame of this model; hence I focus on two stocks of departmental knowledge.

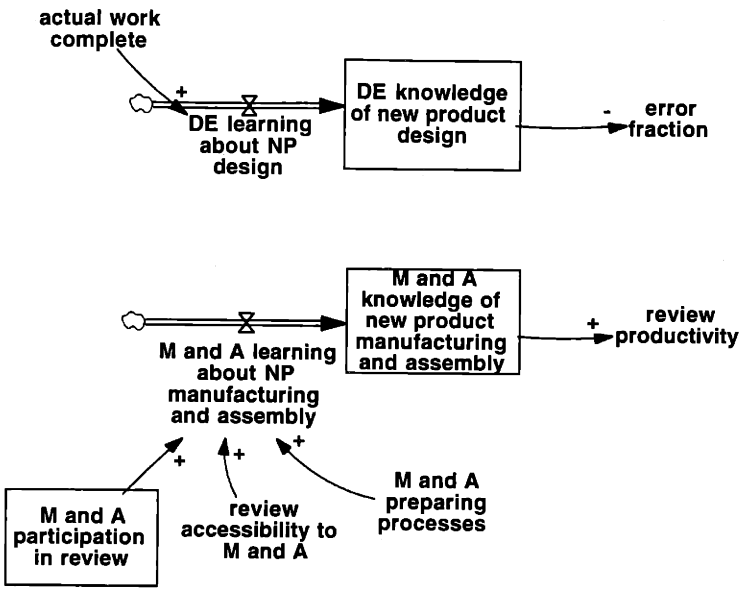

Figure 4.7: Knowledge of new product work

An important reason for representing distinct knowledge accumulations for design engineering and manufacturing and assembly is empirical evidence that suggests these departments accumulate their knowledge about the new product effort from different activities and, further, that their knowledge in turn affects different aspects of product development. Design engineering knowledge, a dimensionless accumulation ranging in value from 0 to 1, increases as design engineers complete design work without error or by correcting identified errors. When design engineers know everything there is to know about a new product's design, they have completed all tasks accurately and DE Knowledge of New Product Design equals 1. As design engineers learn more about a new product's design, they make fewer errors in their work (decreasing the Error Fraction). Also a dimensionless stock ranging in value between 0 and 1, M and A Knowledge of New Product Manufacturing and Assembly can increase based on three factors. As long as manufacturing and assembly representatives are present at a review, the more accessible to them that review is, the more they can learn from it. If representatives from

manufacturing and assembly already have some knowledge about the new product, then they can learn more about producing the new good by thinking through, staging, and documenting potential processes for fabricating parts and assembly components into vehicles. Process preparation often is undertaken by manufacturing and assembly when a prototype build is imminent or in the last few months before the model-year launch. As manufacturing and assembly staff gain understanding of a new product's production processes, they become more effective in identifying latent problems during reviews (i.e., their knowledge increases Review Productivity).

Interdepartmental reviews

As mentioned above, the model represents participation in interdepartmental reviews as a necessary but insufficient condition for manufacturing and assembly learning about new product work. To gain knowledge, the review must also be accessible to plant personnel. The view representing Review Accessibility to Manufacturing and Assembly is shown as a sketch in Figure 4.8. The variable Review Accessibility to M and A is a dimensionless indicator (defined on the interval (0,1]) of how much a review resembles the practices of manufacturing and assembly. It is determined (multiplicatively, equally weighted) by Participation by M and A, and the accessibility to manufacturing and assembly of artifacts, actions, and location, each of which is also a 0-to-1 indicator of that variable's respective resemblance to the artifacts, actions, and locations common to daily work in manufacturing and assembly. Because design engineers are predisposed to stage reviews using work practices with which they are most familiar and the tools at hand, the model represents that a review's location, actions, and artifacts are accessible to manufacturing and assembly to the extent that design engineering effort or managerial policy

make them so. When a method-mandated prototype build occurs, the location, artifacts, and actions take on the maximum value of accessibility to manufacturing and assembly.

For the model I conceptualize two of the four characteristics of reviews as stocks that grow as a result of certain activities accumulating through time. Participation from manufacturing and assembly may increase as a result of plant personnel learning (and retaining—the model assumes there is no forgetting within the time frame of simulation) knowledge about the new product effort through previous reviews, preparing processes, or as a result of effort or managerial policy to have manufacturing and assembly represented at all reviews. An artifact grows more "concrete," relative to its capability to test manufacturing and assembly processes, as design engineers complete its design, or as they make a special effort to obtain prototype hardware to represent incomplete designs. Concrete artifacts for reviews also result from manufacturing and assembly documenting possible procedures for fabricating or assembling components.

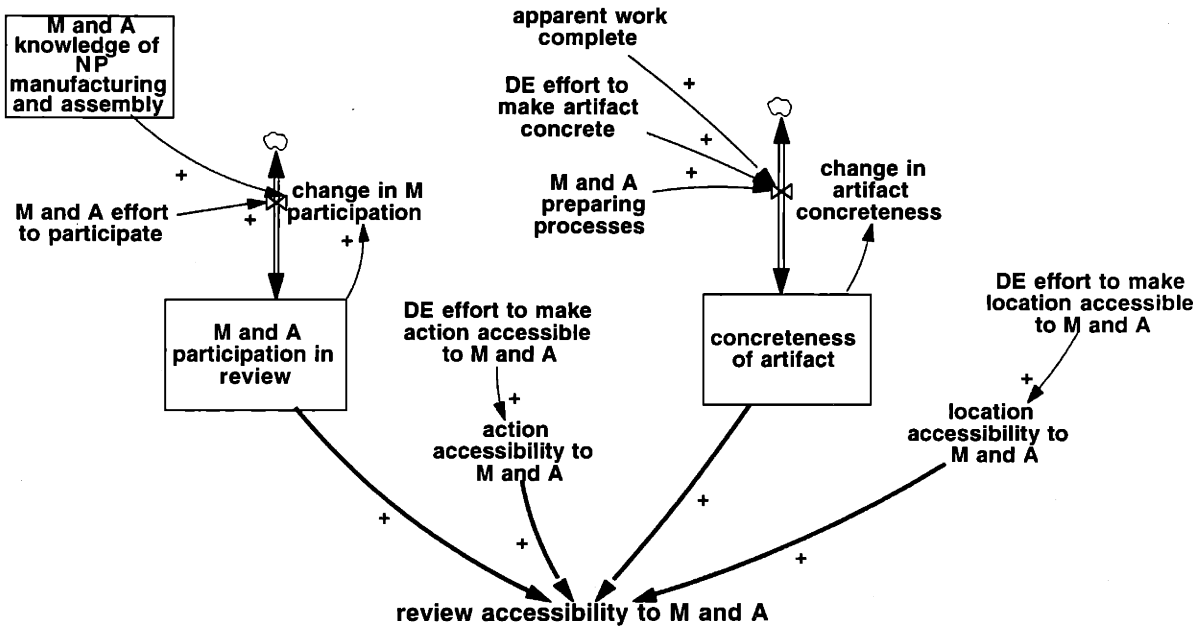

Figure 4.8: Review accessibility to manufacturing and assembly

In the model, as at the Company, if design engineers want to hold a review at a manufacturing plant, they must exert special effort, unless the review is a method-mandated prototype build, in which case the location accessibility to manufacturing and assembly is 1. To assign values, based on various scenarios for reviews, to each of the influences on the review's accessibility to manufacturing and assembly, I drew on my observations of the three types of reviews at the Company. For example, M and A Participation in Review takes on a value of 1 if the plant is well represented at the review, and 0 if no participants from manufacturing and assembly attend. Sparse participation from the plant at a review corresponds to an intermediate value of 0.3 or 0.4. To create values for locations, artifacts, and activities, I ordered examples of these that I had observed in use along a scale from 0 to 1 according to their "distance" from daily practices of manufacturing and assembly. For example, ordinating locations of reviews yields Figure 4.9.

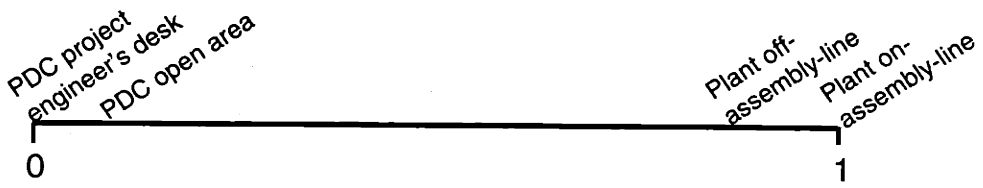

Figure 4.9: Location accessibility to manufacturing and assembly

I show locations as rather polarized between the Product Development Center and the manufacturing plant, based on interviews with both manufacturing and design engineering representatives, who indicated that whether a review takes place on a department's "home field" influences the nature of issues discussed and willingness among participants to speak up on those issues.

Similarly, making a review action or artifact especially accessible to manufacturing and assembly requires effort from design engineering, unless a method-mandated prototype build determines that the actions will include assembling a prototype vehicle from hardware. Figure 4.10 shows my ordination of observed actions during reviews. Ordering the "concreteness" of artifacts (compared to a finished product) used in reviews produces a 0-to-1 scale shown in Figure 4.11.

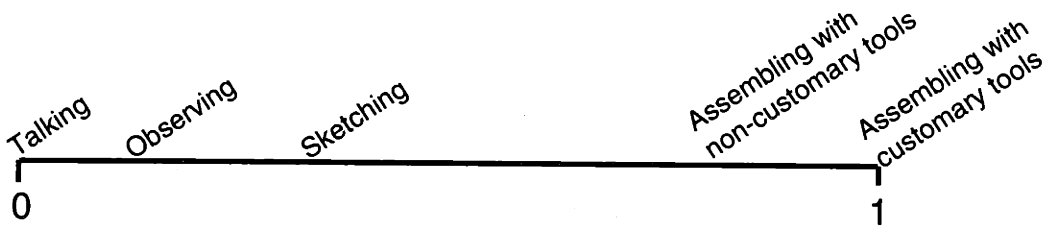

Figure 4.10: Action accessibility to manufacturing and assembly

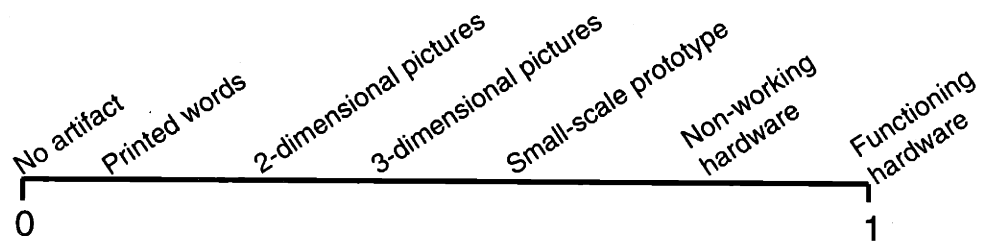

Figure 4.11: Concreteness of artifact relative to completed good

At the Company, both design engineering and manufacturing and assembly staff place a high value on being able to work with prototyped hardware during development, but this is particularly true of plant personnel. As Bob, a manufacturing engineer, said in characterizing manufacturing's appreciation for tangible artifacts: "Until I hold it in my hand, it's not real" (Interview notes, BL. 1.7).

In reality the aspects participation, artifacts, actions, and location affect each other. If a review takes place at the plant, for example, participation from manufacturing and assembly is likely to be much higher than if it occurs at the Product Development Center. As mentioned above, however, for ease in explicating model behavior, I do not represent interdependencies among these. Instead I allow each of them to operate as independent levers of "effort" applied to each aspect during simulations of various scenarios how to conduct reviews. A review's accessibility to manufacturing and assembly affects the percentage of latent problems in new product development work identified during a review. It also affects the productivity of a review, through the accumulated knowledge of members of manufacturing and assembly participants.

New product development work

The model sector representing new product work and progress is shown as Figure 4.12. A rich body of system dynamics literature has studied the dynamics of project management (Cooper, 1980; Richardson and Pugh, 1981; Ford and Sterman, 1998), and a standard model structure for representing the rudiments of projects has emerged (Sterman, 2000), which I adopt here. New product development tasks can exist in one of four states: Work to Do, Undiscovered Rework, Known Rework, or Work Done Correctly. When a new project is initiated, no development work has yet been done, so all tasks (Initial Scope) are in the Work to Do accumulation. As design engineers perform work—I assume for simplicity that all this new product work is done (or re-done) by design engineers—tasks move to the stock Work Done Correctly, with a probability of 1-. Error Fraction. The presence of the Error Fraction indicates that it is impossible to perform all tasks correctly on the first try. Tasks performed incorrectly

require rework, but reviews with manufacturing and assembly are necessary to identify which tasks must be redone. Hence as design engineers perform Work to Do, tasks enter the accumulation Undiscovered Rework with a probability of Error Fraction.

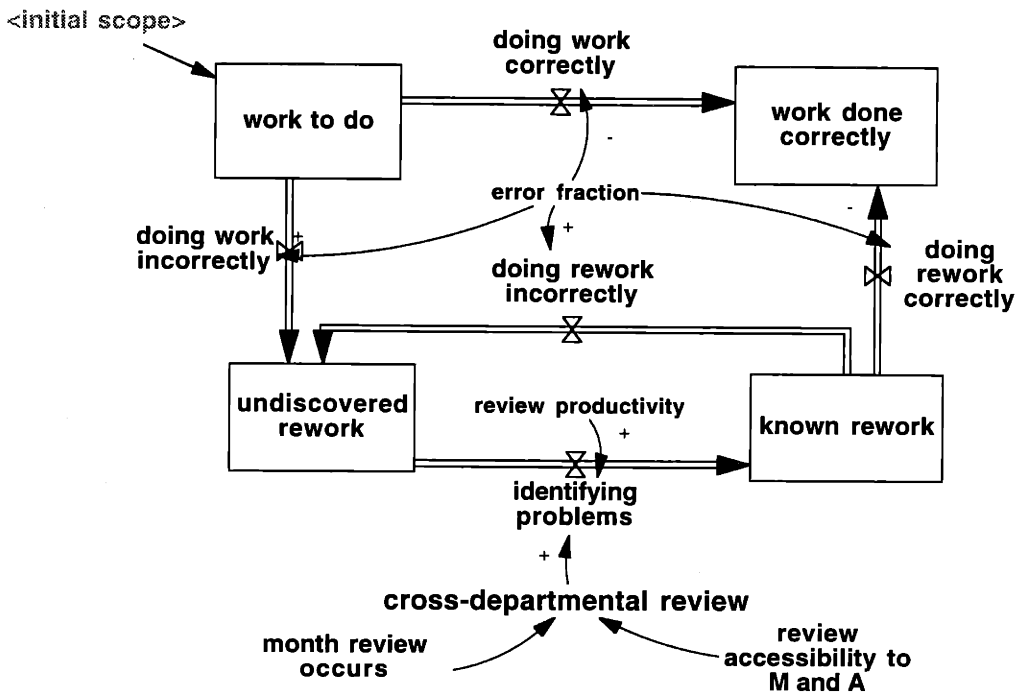

Figure 4.12: New product work

To simplify the model and focus on the effects of interdepartmental reviews, I assume that tasks needing rework are discovered only through reviews with manufacturing and assembly, which identify problems in the work. When a review takes place, it is not a given that all the problems in the work-to-date will be discovered at that time. The rate of Identifying Problems depends on the extent to which the review characteristics resemble the practices of the plant and on the productivity of the participants in the review. Influences on Review

Accessibility to M and A and Review Productivity have been discussed above. The variable Month Review Occurs serves as a lever with which to try different timing of reviews.

Once rework is discovered, design engineers can then perform tasks again. When they do, with probability Error Fraction tasks will be performed incorrectly again and re-enter the accumulation of Undiscovered Rework; and with probability of 1-Error Fraction they will enter Work Done Correctly. In this simple model tasks performed accurately never leave the stock Work Done Correctly. As more of the new product work is completed correctly, the Error Fraction is reduced, reflecting that design engineers make more mistakes at the beginning of the development cycle, when little is known about the end-product, and fewer mistakes as more elements of the design are well defined and verified.

This representation drastically simplifies the iterative, messy work of identifying problems in new product efforts. In Project Hook (described in appendices A, B, and C following this chapter), for example, insufficient filtering in the fuel pump probably contributed to problems manifesting in the carburetor. But while some people knew about "junk in the carburetor" and others knew about incorrectly sized filter mesh in the fuel pump and still others knew of test vehicle engines "stumbling," these were not connected until the problems had persevered for a few months. A complicating factor, a contaminated fuel storage tank at one of the test facilities, made it still more challenging to identify incontrovertibly "the problems" and "the solutions" in the products under development. The model also generously assumes that engineering staff is always adequate. Other research has studied effects of inadequate staffing (see, for example, Repenning, 2000; Black and Repenning, 2001; Repenning, Gonçalves, and Black, 2001). If the model, which represents new product activities in simplified ways, reproduces problematic behavior observed at the field site (the Current reference mode), then it

provides a reasonable hypothesis of the relationships among work-to-do, knowledge about new product work, and interdepartmental review that, taken together, through time, generate "late changes." Relaxing simplifying assumptions to account for scarce resources in engineering and manufacturing and assembly or to represent the likelihood that sources of a problem are often not identified immediately and correctly merely increases the probability of design alterations late in the development process.

A couple of variables, shown in Figure 4.13, keep track of progress in new product development work. Apparent Work Complete is the percent of work that design engineers think that they have completed, or (Work Done Correctly + Undiscovered Rework) / (Work to Do + Undiscovered Rework + Known Rework + Work Done Correctly). This is an optimistic view, reflecting a common bias (observed both in the field and in everyday life) toward believing that any work done is work done correctly, until someone else points out the need for rework. Actual Work Complete, however, accounts for the fact that not all tasks are performed correctly the first time and is the percent of tasks done correctly at any one point in time (Work Done Correctly divided by the sum of all four accumulations of tasks). Of course, except in the world of simulation and modeling, we seldom know while we are working on a project the value of Actual Work Complete. Finally, to compare the simulated problems with the pattern of open concerns at the Company, the Fraction of New Product Work Identified as Problems is the percentage of all tasks in the model year currently identified as needing rework (Known Rework divided by the sum of all four accumulations of tasks).

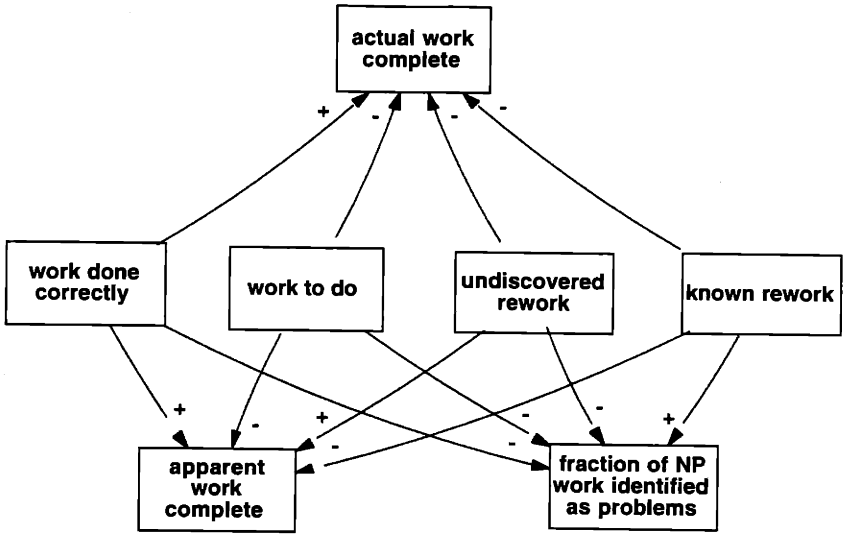

Figure 4.13: Keeping track of progress

4.5 Model simulations

I first verified that the model simulates appropriately under a variety of tests (Sterman, 2000), checking that it produces reasonable behavior in both physically conceivable and inconceivable scenarios. Then I explored throughout the simulated development cycle the behavior of variables of interest—such as Actual Work Completed and the Fraction of Problems in New Product Work (which is analogous to the Company's log of open concerns in new or changed parts). Below I present a base case simulation predicated on the CPPDM's prescribed approach to cross-functional interactions; a general exploration of the range of behavior under various scenarios for review timing and accessibility to manufacturing and assembly; and a simulation producing the Ideal pattern of design changes desired by the Company.

Simulating the base case: The Current CPPDM approach to reviews

To establish a base case simulation, I created as input to the model a policy, or stream of decisions, for conducting interdepartmental reviews that mimics the timing and nature of interdepartmental reviews currently taking place at the Company as it implements the CPPDM instructions for cross-functional interactions. When this scenario, called Current, is simulated, the model generates a pattern of design changes that qualitatively resembles the two-humped pattern of late changes abstracted from field data and depicted in Figure 4.5 above.

The Current policy (timeline shown in Figure 4.14 below) consists of four reviews. In this scenario, design engineering applies about half its effort to making the review accessible to manufacturing and assembly during the months when the reviews occur, and manufacturing and assembly applies a 50 percent effort to attending the reviews not held at the plant. As a result, in this scenario the first two reviews are low in accessibility to manufacturing and assembly (about 0.1 on a continuum from 0 to 1) and take place during the nineteenth and fifteenth months before launch. These first two reviews correspond well to project design reviews and mock-up / model-year reviews that take place at the Product Development Center with minimal or moderate participation from manufacturing, consisting of a design engineer's or platform leader's presenting slides with words and two- or perhaps three-dimensional sketches and engaging participants in some question-and-answer dialogue. The last two reviews simulated are high in accessibility to Manufacturing and Assembly (1.0 on a 0-to-1 continuum) and take place in the eleventh and fifth months before launch. These reviews correspond to the DIB and FPE prototype builds that take place on the assembly lines at the manufacturing facilities, with manufacturing engineers and assembly workers involved in putting together vehicles embodying new product development work scheduled for the next launch.

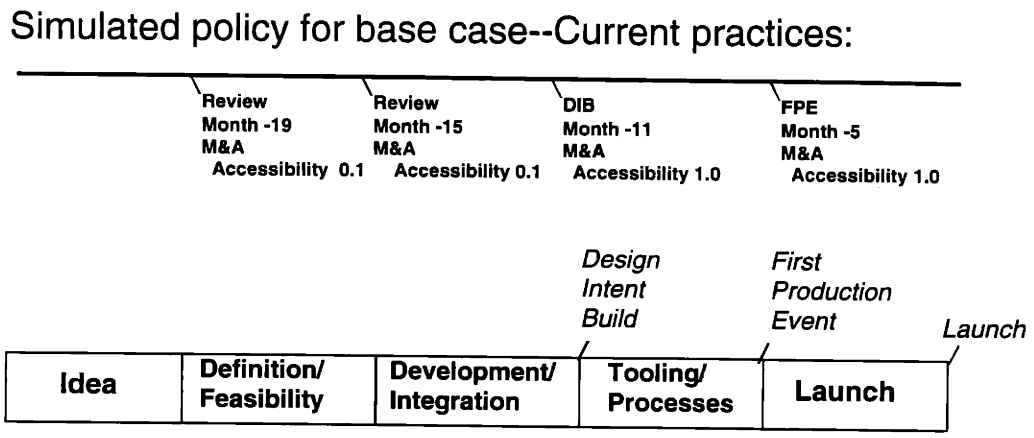

Figure 4.14: Current policy for interdepartmental reviews

The Current policy of interdepartmental reviews generates the simulated patterns of apparent and actual progress in new product development work shown in Figure 4.15. Apparent Progress (the first trajectory in the graph below) grows quickly as design engineers rapidly deplete the accumulation of Work to Do. Actual Progress (the second simulated pattern in Figure 4.14), meanwhile, plateaus after the nineteenth month before launch, as latent problems in the work remain unidentified through the first two reviews and therefore unresolved. Since the first two reviews, patterned after the project and mock-up / model-year reviews at the Product Development Center, do not much resemble practices of manufacturing and assembly, few problems are discovered, and Apparent Progress dips only slightly on these occasions. We might think of the time between the twentieth and the eleventh months before launch as "wasted" because Actual Progress improves little during this period.

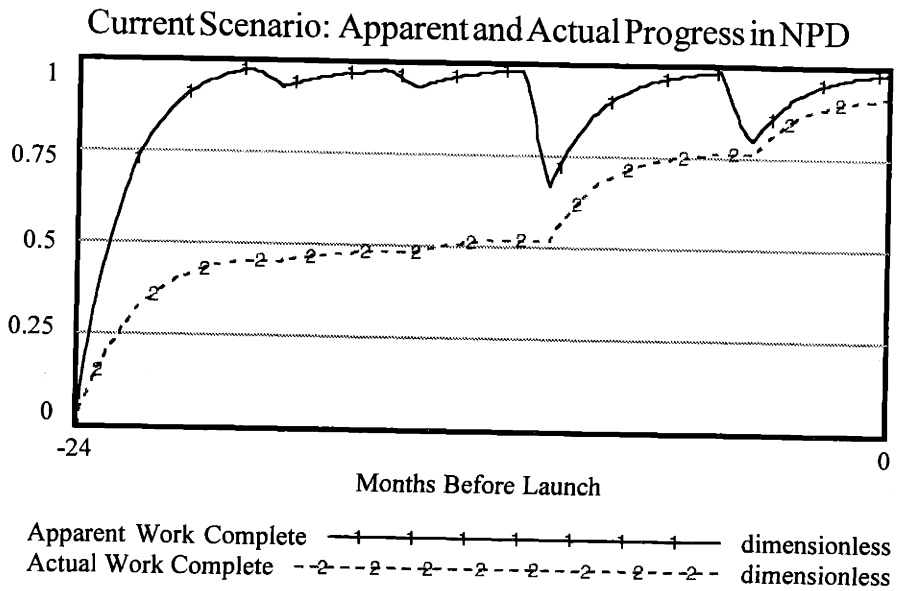

Figure 4.15 Simulated apparent and actual progress under Current policy

When the first prototype build takes place in the eleventh month before launch, however, Apparent Progress falls sharply as many problems are identified (see Identifying Problems graph, Figure 4.16, below).

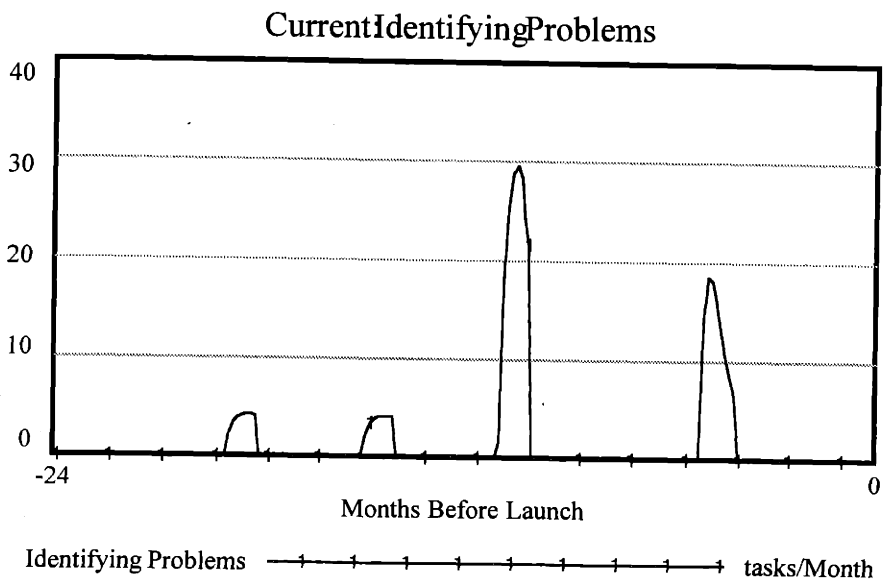

Figure 4.16: Simulated rate of identifying problems under Current policy

As design engineers correct identified problems, Apparent Progress and Actual Progress both increase. Apparent Progress increases more than Actual Progress because the rework also contains problems (see the sharp drop and subsequent increase in Undiscovered Rework after the eleventh month before launch, the first trajectory in Figure 4.17, below), which then remain latent until the next prototype build discovers them.

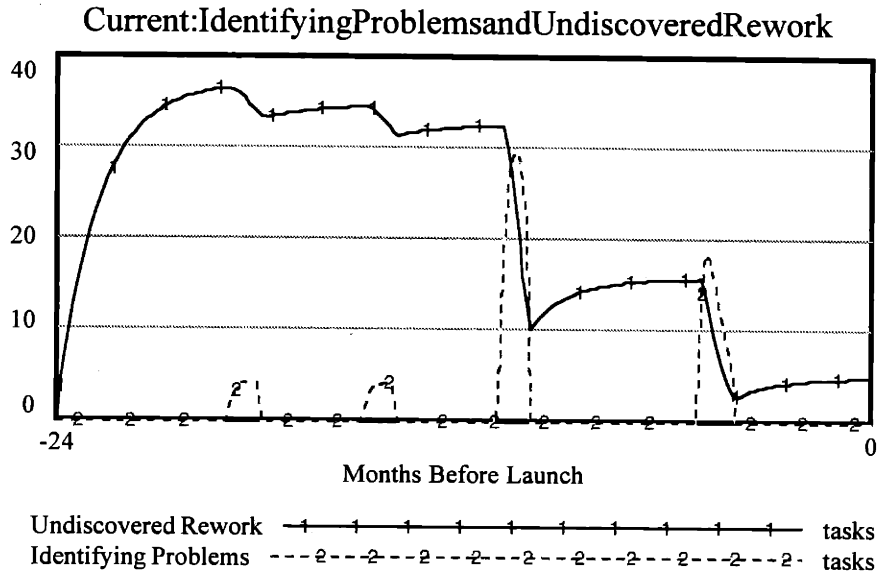

Figure 4.17: Simulated rate of Identifying Problems and accumulation of Undiscovered Rework under Current policy

Initially Undiscovered Rework grows rapidly as design engineers work quickly but with a high probability of errors. The first two reviews discover a few problems, and so the accumulation of Undiscovered Rework dips slightly, but it falls sharply only after reviews high in accessibility to manufacturing and assembly take place in the eleventh and fifth months before launch. Efforts to correct the problems identified by the reviews accessible to manufacturing and assembly in eleventh and fifth months before launch lead to a two-humped pattern during the last months of the simulated development cycle (Figure 4.18), a pattern qualitatively similar to the "late changes" observed in the field (Figure 4.19).

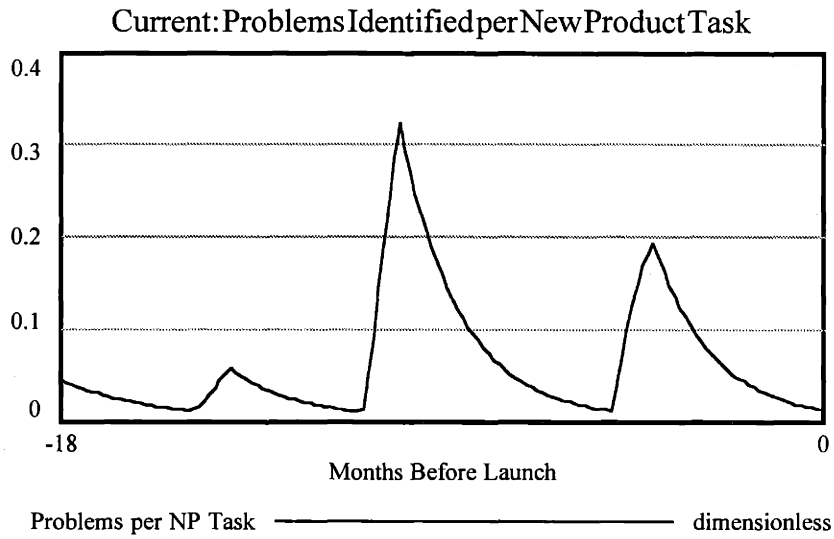

Figure 4.19: Simulated pattern of Problems per New Product Task under Current policy

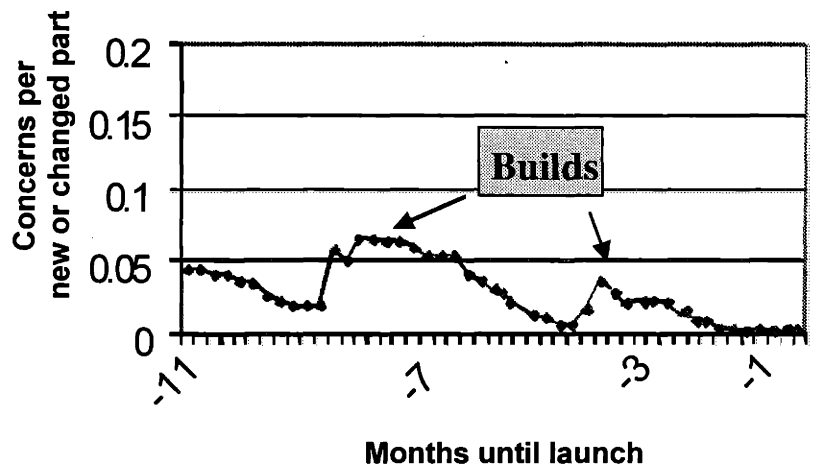

Figure 4.19: Pattern of late changes observed in the field

The simulated pattern of Problems Identified per New Product Task is much more pronounced than actual because the model assumes that problems are identified only through interdepartmental reviews, when in reality activities such as laboratory and road tests also identify problems. This assumption, which simplifies the model and provides focus on effects of interdepartmental reviews, exaggerates the amplitude of the pattern of problems emerging from the prototype builds, during which manufacturing and assembly staff are able and inclined to

identify latent problems in the product. The model also assumes problems are immediately identified during interdepartmental reviews (as participation by and accessibility to manufacturing and assembly staff permit); in reality problem identification probably takes some period of review time, and additional problem identification may continue after a review as a result of problems recognized during the review. This simplifying assumption skews to the left each rise in Problems Identified in the graph shown. Relaxing this assumption would mean that problems in new product work would be identified later and so resolved later than portrayed in the simulation (worsening the organizational outcome).

The Current simulation suggests that following the CPPDM's guidance for holding reviews does *not* prevent late changes. It is possible to hold many interdepartmental reviews that meet the stipulations of the prescribed method and are nevertheless low in accessibility to manufacturing and assembly and so facilitate little problem identification. For example, a simulation (not shown here) of twice as many reviews low in accessibility to M and A in the months before the DIB and FPE builds has almost no effect on reducing the amplitude of the two-humped pattern of late problems identified. Thus the Current simulation of late changes can result from *following* the CPPDM method of holding earlier reviews, such as the project and mock-up / model-year reviews, using artifacts and activities and locations accessible to design personnel, and later reviews, such as prototype builds, using artifacts and activities and locations highly accessible to manufacturing and assembly. The implication is that design changes occurring late in the development cycle may not result from employees' *not* following the CPPDM method, as is sometimes attributed at the Company. Nor do late changes result from a lack of effort or conscientiousness on the part of design engineers, as is occasionally voiced by both design and manufacturing staff.

The Current simulation calls into question the engineering vice-president's advocacy of "virtual everything" during development, the use of CAD images, rather than prototypes or even print-outs of drawings, in interdepartmental reviews. Since only the Product Development Center is equipped with a CAD projection system, the managerial policy necessitates that reviews take place away from manufacturing facilities. Such a policy is considered desirable by most; it makes use of advanced design engineering tools and perhaps reduces costs early in development by eliminating construction of prototype hardware that will not be used again. But it also affects the ability of non-design-engineer participants to represent their knowledge of the work at hand, simply because their work does not allow them to become familiar with the tools used in the review. Both the "physics" of easily creating tangible prototypes only *after* much of the design work is completed and organizational patterns that keep manufacturing effectively distanced from new product efforts *until* prototypes take shape at the plant help perpetuate changes late in the development cycle.

If we look at the Current simulation's view of new product knowledge (Figure 4.20), we see that design engineering knowledge grows with initial design efforts but plateaus as the early reviews leave many problems undiscovered and unaddressed. Plant personnel acquire some knowledge about manufacturing and assembling the new product from early reviews but learn much more when the third review—the first prototype build—takes place in the eleventh month before launch. The later reviews, high in accessibility to manufacturing and assembly, identify problems, which design engineers then address through design changes. Under the Current policy, by the time the new product launches, the organization has learned nearly everything it needs to know about designing and manufacturing it.

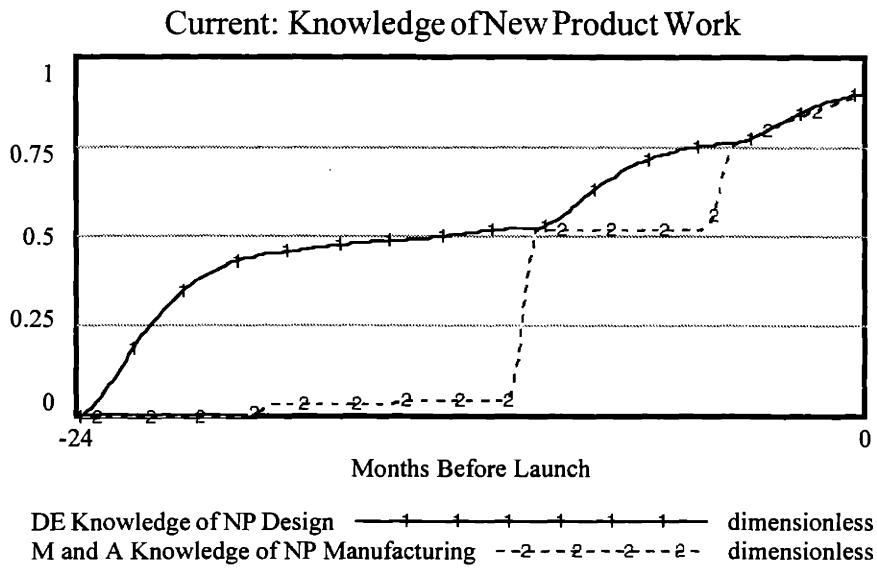

Figure 4.20: Simulated knowledge of new product work under Current policy

The gap between design and manufacturing knowledge from the beginning of the development cycle until the eleventh month before launch portrays graphically that early reviews inaccessible to manufacturing and assembly (representing reviews held at the Product Development Center) do not substantively increase plant personnel's knowledge of the new product. The challenge, then, lies in identifying artifacts and actions that can close the gap between the two groups' knowledge of new products early in the development cycle.

Exploring variations in nature and timing of reviews

With the model it becomes feasible to explore more generally the effect on new product development of variations in the timing of reviews and their accessibility to manufacturing and assembly. Below are several graphics summarizing the end-state of a series of simulations, each one with a different degree of review accessibility to manufacturing and assembly and different review timing in the development cycle. In each chart below, the vertical axis shows the simulations' percent of actual work completed at launch; the horizontal axis extending to the

right shows the month in which the review occurs; and the axis extending "into the page" indicates the reviews' accessibility to manufacturing and assembly.

One review, varying timing and accessibility to manufacturing and assembly

The first series of simulations have as input only one review. Each simulation varies either the review's accessibility to manufacturing and assembly or the month in which it occurs. A few basic conclusions can be drawn from the resulting surface, shown in Figure 4.21. First, we can see that a review more accessible to manufacturing and assembly always leads to a greater percentage of actual work completed by launch. Second, we can conclude from the downward slope on either side of the outcomes of reviews highly accessible to manufacturing and assembly that the review can be too early or too late to aid performance. If, for example, a review accessible to manufacturing and assembly takes place 21 months before launch, the actual work completed at launch is lower than if the same kind of review occurs at 19 months before launch. Thus a review accessible to manufacturing and assembly very early in the development process may reveal latent problems in the design—but since not all the design work has been completed before the review occurs, many more problems are created after the review and remain unidentified and unresolved at launch. On the other hand, if a review accessible to manufacturing and assembly occurs three months before launch, it may identify latent problems in the design work-to-date; but, once it does, there is not sufficient development time remaining to correct the identified problems before launch.

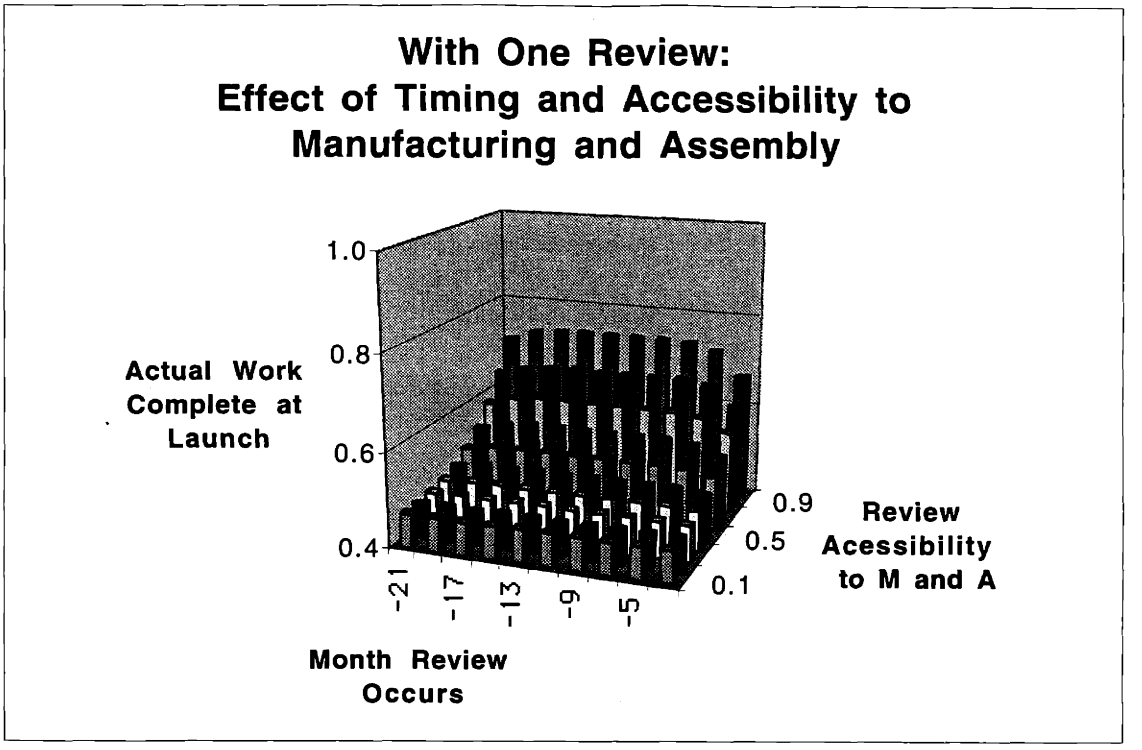

Figure 4.21: One review's effect on actual work complete at launch

Finally, we see from the surface that one review is not sufficient to achieve 100 percent actual work complete; no point on the graph's surface represents actual work complete greater than 73 percent. That is because a single review, even if accessible to manufacturing and assembly, does not necessarily identify all latent problems in new product development work, and the subsequent rework to address problems also contains errors, which remain undiscovered and unaddressed if there is no subsequent review.

Two reviews, varying timing and accessibility to manufacturing and assembly

The next chart, Figure 4.22, depicts a series of simulations in which two reviews are conducted during the development cycle. *Within* each simulation, the two reviews, five months apart, embody the same degree of accessibility to manufacturing and assembly. *Across*

simulations, I vary the reviews' accessibility to manufacturing and assembly (between 0.1 and 1.0), as well as their timing in the development cycle.

There is significant benefit from holding a second review. The best performing simulations, those having the most accessible reviews in the middle months of development, show more than 90 percent work complete at launch. The improvement increases as reviews are more accessible to manufacturing, and the steeper slope of simulation outcomes based on reviews of 0.5 accessibility to 1.0 accessibility indicates that the effort to make a review *very* "realistic" to manufacturing and assembly pays off in increased problem identification and resolution.

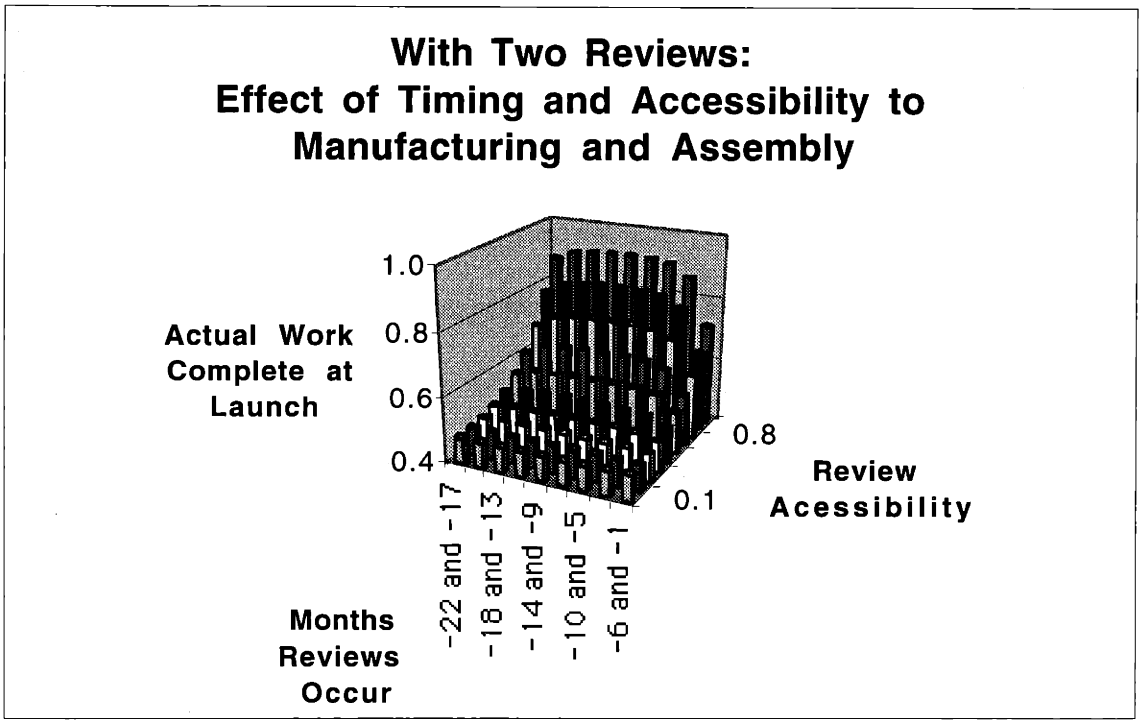

Figure 4.22: Two reviews' effect on actual work complete at launch

The surface suggests there is a higher penalty for holding the reviews too late than for holding them too early. If two reviews highly accessible to manufacturing and assembly are held

in the first seven months of development, 87 percent of actual work is completed by launch, but if the same types of reviews take place in the last six months, the outcome is just over 70 percent. As in the previous series of simulations, holding reviews in the middle months of development leads to the highest percentage of actual work complete at launch because sufficient work has been completed to create latent problems to find, and yet there is still time after the reviews to address the problems before launch occurs.

Three reviews, varying timing and accessibility to manufacturing and assembly

Figure 4.23 depicts a series of simulations in which three reviews are conducted during the development cycle. *Within* each simulation, the three reviews, five months apart, offer the same degree of accessibility to manufacturing and assembly. *Across* simulations, I vary the reviews' accessibility to manufacturing and assembly (between 0.1 and 1.0), as well as their timing in the development cycle.

Three reviews of very low accessibility to manufacturing and assembly leave 50 percent of the latent problems undiscovered at launch, regardless of when they occur, but three reviews of very high accessibility to plant personnel allow discovery and resolution of about 95 percent of latent problems in the new product.

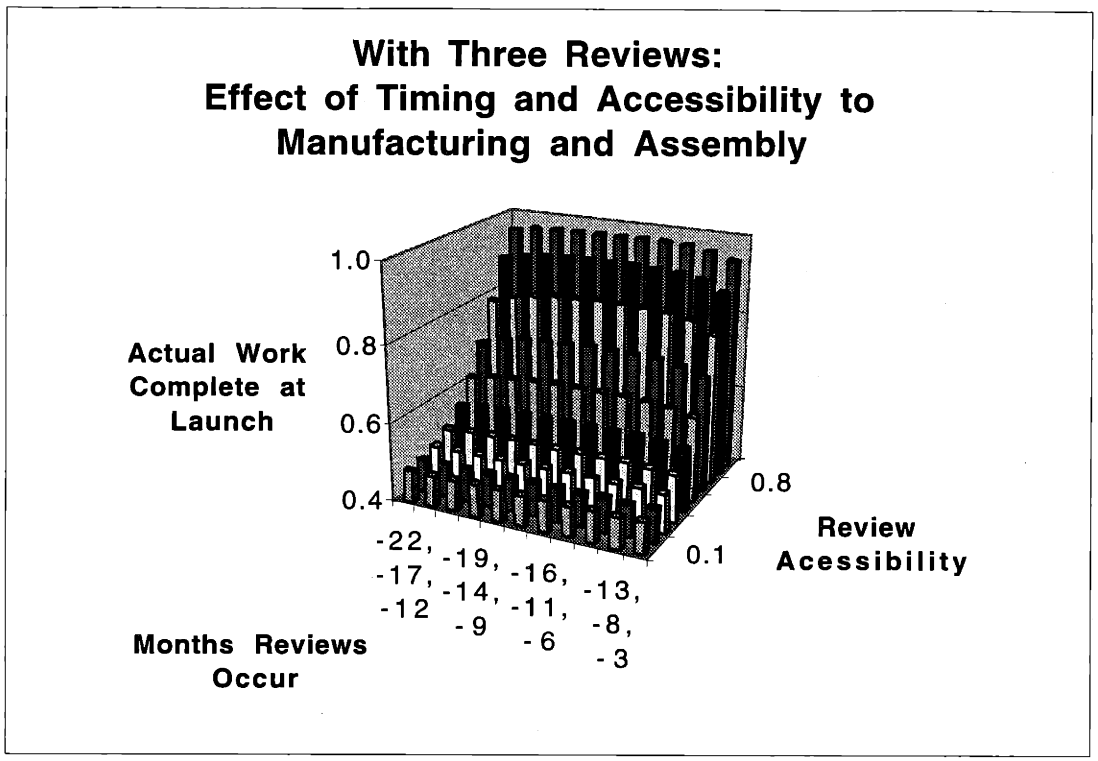

Figure 4.23: Three reviews' effect on actual work complete at launch

Again, in the simulated world, *when* the reviews occur matters less than their accessibility to manufacturing and assembly. If the last review takes place within six months of launch, however, actual work complete at launch is less than if it occurs earlier. This results from insufficient time before launch to address the problems identified during the last review.

The Ideal scenario

With a general understanding of the effects of reviews on new product development work provided by the explorations above, I searched for a simulation whose reviews' nature and timing would produce the Ideal pattern of problems identified depicted in Figure 4.5. Setting aside for the moment notions of what is currently believed possible or expected at the Company, I wanted to assess whether reviews highly accessible to manufacturing and assembly (however

that might be defined) staged earlier in the development cycle could indeed produce the desired pattern of design changes concluding by the time the DIB occurs. The following is one effective policy, though certainly not the only, policy to produce a pattern similar to the Ideal reference mode.

This policy generating the Ideal pattern (timeline shown in Figure 4.24) calls for three reviews accessible to manufacturing and assembly to take place before the DIB and FPE prototype builds mandated by the CPPDM.

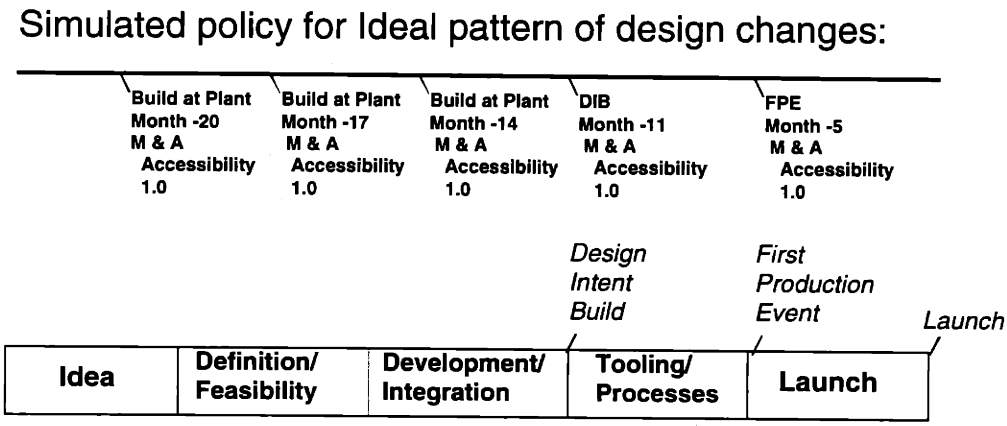

Figure 4.24: One simulation to generate the Ideal pattern

This scenario creates a pattern of design changes (shown in Figure 4.25) that largely concludes before the Design Intent Build takes place 11 months before launch. In this simulation, both the DIB and FPE uncover some problems, which lead to additional design changes, but they are relatively few.

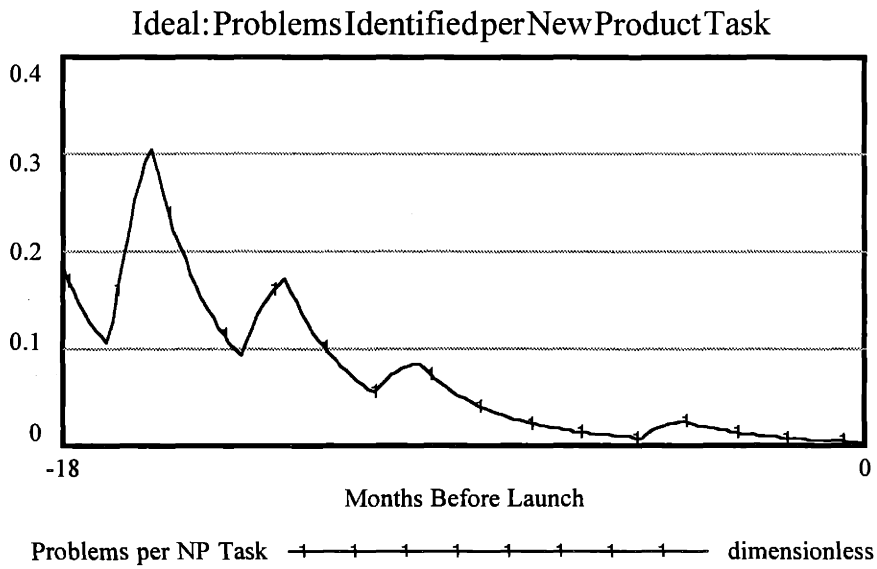

Figure 4.25: Simulated Problems per New Product Task under the Ideal scenario

In the Ideal scenario, Apparent Work Complete (shown with Actual Work Complete in Figure 4.26) appears much more sporadic, as each of the early reviews discover rework, and engineers learn that work believed complete must be done again. Juxtaposing the graph for Review Accessibility to Manufacturing and Assembly (Figure 4.27) with the simulations of progress reveals that the highly accessible reviews trigger the downturns in Apparent Work Complete.

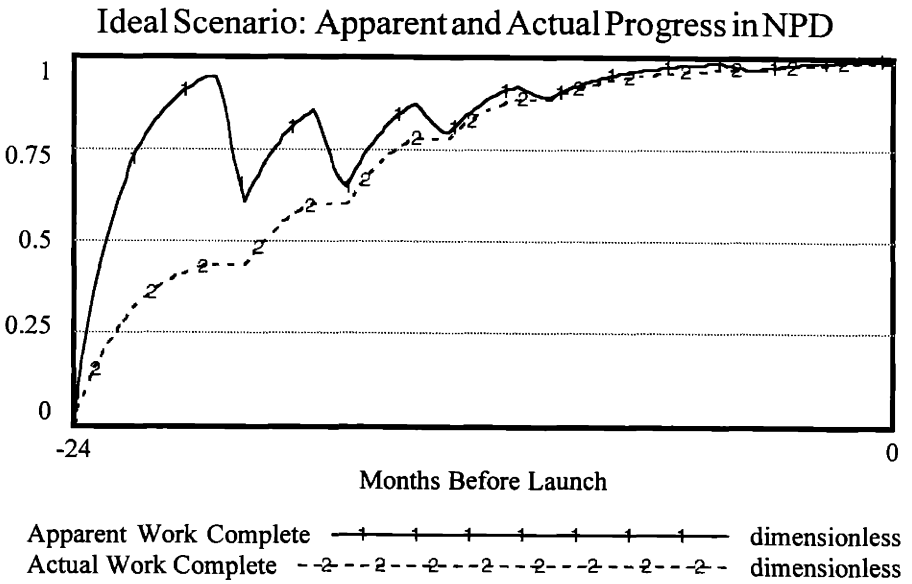

Figure 4.26: Simulated Apparent Work Complete and Actual Work Complete under the Ideal scenario

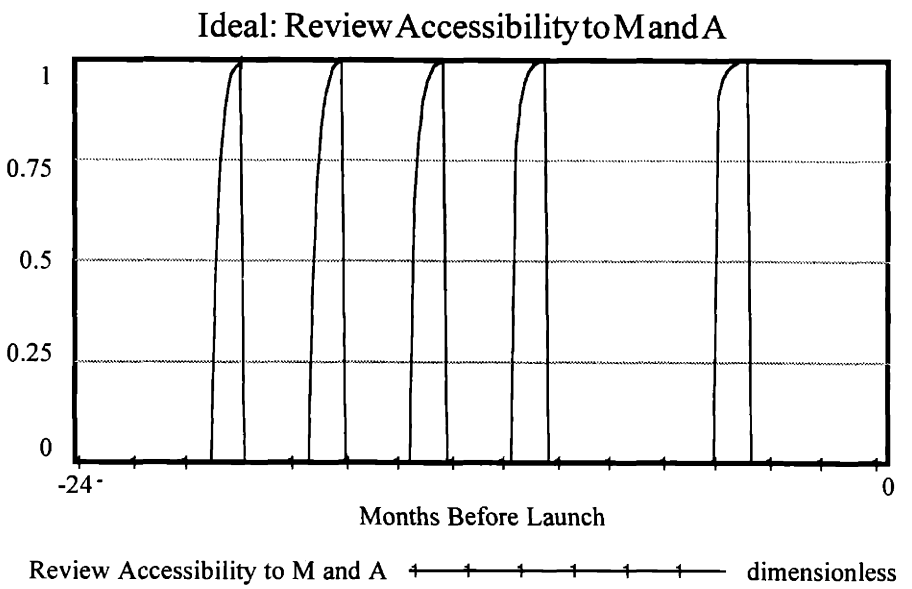

Figure 4.27: Simulated Review Accessibility to Manufacturing and Assembly under the Ideal scenario

Each of the early reviews identifies a significant number of problems, and Undiscovered Rework (Figure 4.28) gradually decreases through the first three reviews accessible to manufacturing and assembly.

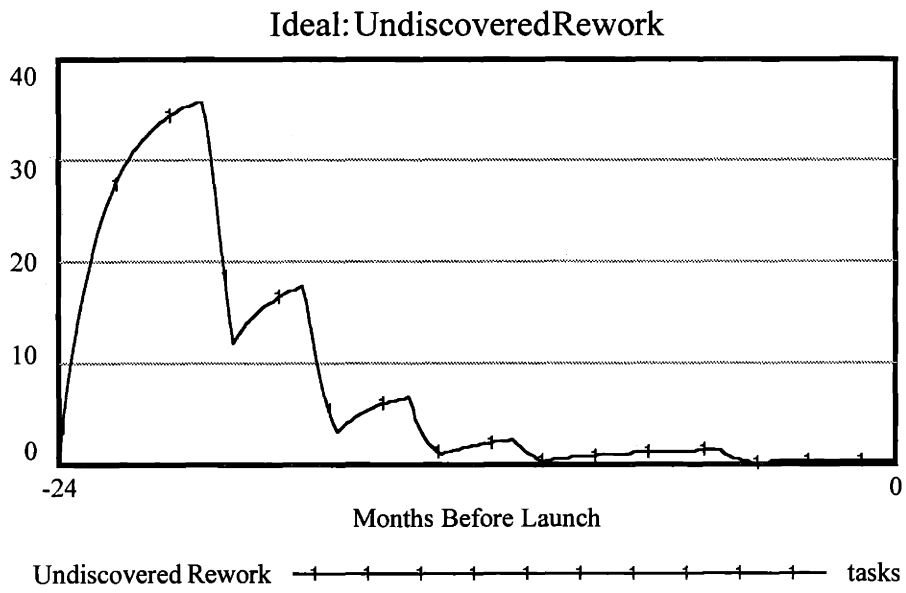

Figure 4.28: Simulated Undiscovered Rework under the Ideal scenario

Actual Work Complete in the Ideal scenario, however, maintains a steady climb through the first half of the 24-month development cycle, and by the time the CPPDM prototype builds take place in the eleventh and fifth months before launch, actual and apparent progress are virtually identical and very close to 100 percent.

If we consider the model's accumulations of knowledge about new product work (shown in Figure 4.29), we can see that in the Ideal scenario the early reviews accessible to manufacturing and assembly serve to educate plant personnel about new product manufacturing issues. As manufacturing staff participate in the reviews, they identify problems, and design engineers learn more about the new product design as they address problems through rework.

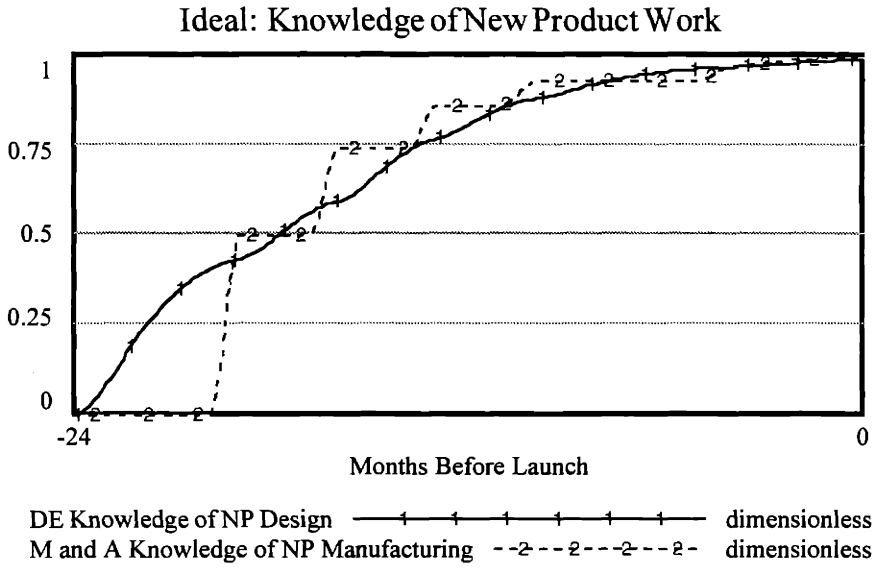

Figure 4.29: Simulated knowledge of new product work under the Ideal scenario

Thus with participation from manufacturing and assembly in early reviews, design engineering knowledge steadily climbs through the first two-thirds of the development cycle. In the Ideal scenario, both design engineering and manufacturing and assembly approach 100 percent of possible knowledge about their respective responsibilities for the new product effort well before launch. Moreover, the early reviews accessible to plant personnel lead manufacturing and assembly to do preparatory process work for the new product efforts, whereas in the Current simulation, little process preparation occurred until the method-mandated prototype builds, as shown in Figure 4.30.

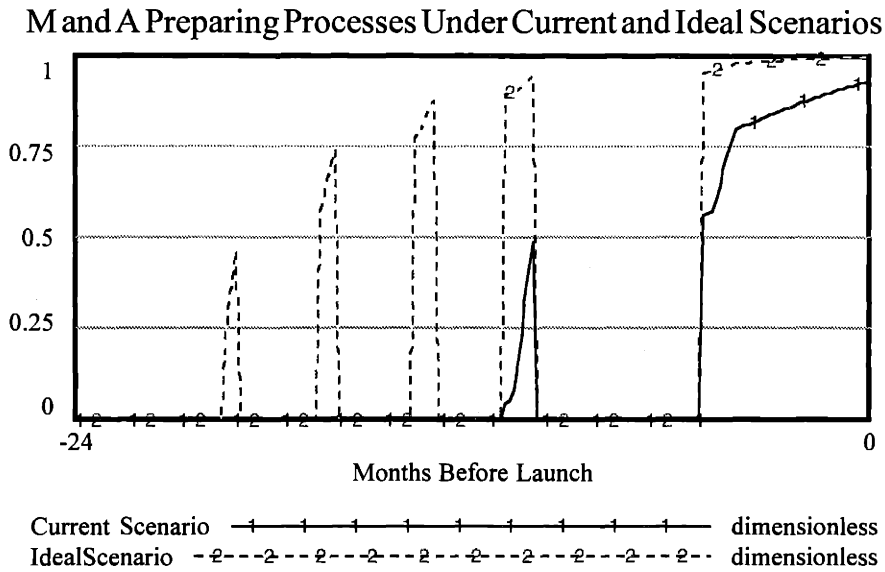

Figure 4.30: Comparison of simulated process preparation by manufacturing and assembly under Current and Ideal scenarios

Comparing the Current and Ideal scenarios (as in Figure 4.31) reveals that Actual Work Complete in the Ideal simulation, in which three reviews accessible to manufacturing and assembly take place early in the development cycle, is much higher after month –19, or 19 months before launch. In the Current scenario, the later reviews accessible to manufacturing and assembly do not allow the organization to regain completely the ground lost earlier in the development cycle when early reviews left many problems undiscovered.

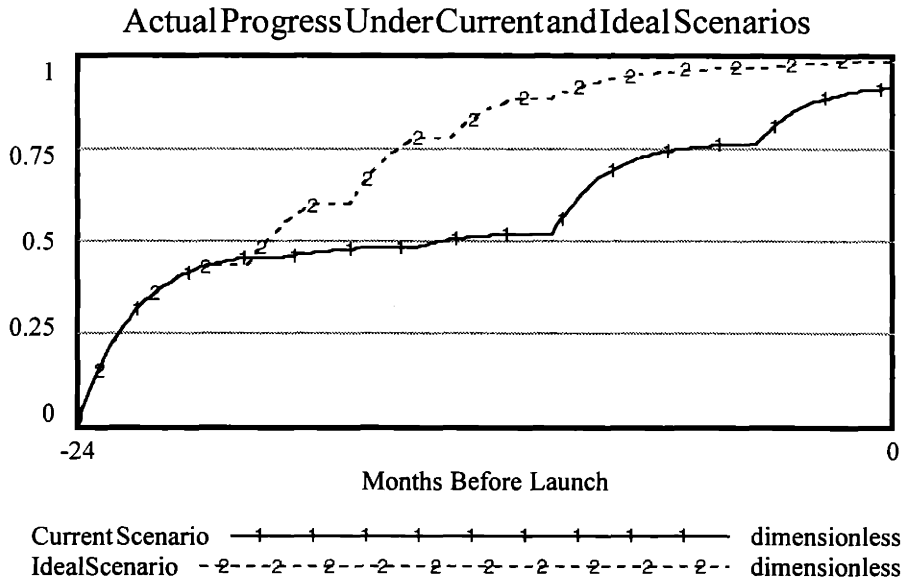

Figure 4.31: Simulated Actual Work Complete under Current and Ideal scenarios

While the trajectory of Actual Work Complete in the Ideal scenario is clearly preferable to that in the Current simulation, in practice it is difficult to assess actual progress real-time. Comparing the two simulations' apparent progress (shown in Figure 4.32) suggests that a practice of early reviews accessible to manufacturing and assembly creates a worse-before-better situation, as viewed by design engineering. Apparent Work Complete in the Current scenario looks excellent through the first half of the development cycle; early reviews reveal few problems in design, and the new product effort appears well managed in its first year of development. The Ideal simulation creates a far less desirable picture. Consider that in the Ideal scenario the design engineers are engaging manufacturing and assembly in early reviews accessible to manufacturing and assembly, perhaps interrupting their responsibilities for current production at the plant, and each review identifies many problems. It might seem that the design engineers are irresponsible, taking plant personnel's time from current production to look at new

product work that, judging from the number of problems identified, is clearly not ready for review.

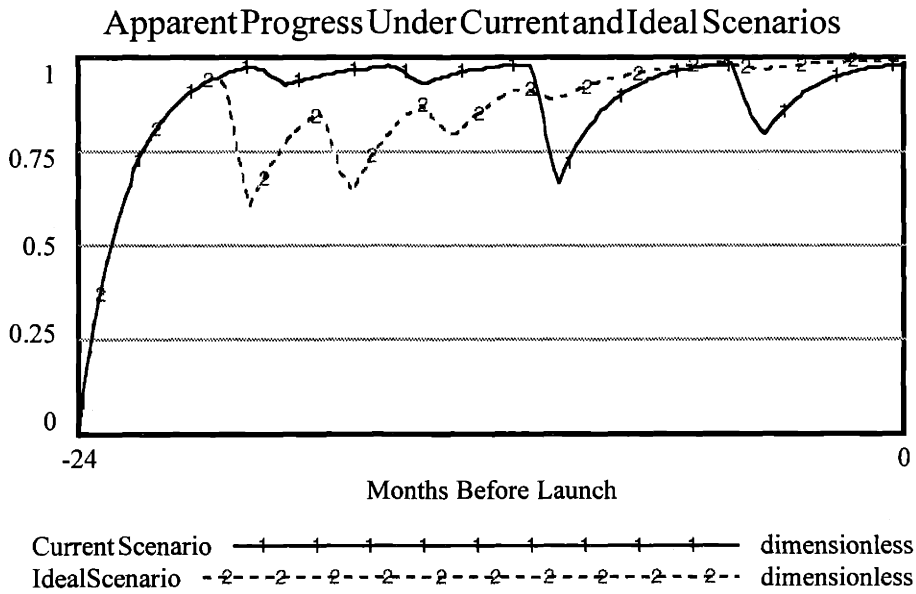

Figure 4.32: Simulated Apparent Work Complete under Current and Ideal scenarios

But from the perspective of manufacturing and assembly, the Ideal scenario may comprise a "better before better" situation. As Figures 4.29 and 4.30 suggest, the early reviews accessible to manufacturing and assembly staff educate them about forthcoming new products and are "concrete" enough to engage plant personnel in planning and developing fabrication and assembly processes much earlier in the development cycle. It is possible, however, that manufacturing and assembly also view the large number of problems emerging during early reviews as indicative of poor product design and poor project management; that is, plant personnel could view the early reviews engaging their attention and resources as "time-wasters," since the artifacts are not representative of the end-product to be launched. Only after the DIB in month –11, when few new problems are identified, does it become clear to both design

engineering and plant personnel that a practice of early reviews accessible to manufacturing and assembly pays dividends over the Current scenario.

Is the Ideal possible?

Given that the simulated Ideal policy produces a more desirable pattern in design changes (as based on the Ideal reference mode, Figure 4.5), it is worth considering what types of reviews accessible to manufacturing and assembly might be staged early in the development process and what social dynamics would support their execution.

Observations at the Company suggest that prototype builds at the plant comprise one form of review accessible to manufacturing and assembly, and it is worth noting that prototype builds early in development are not inconceivable. Matt, the platform leader discussed at the end of Section 4.3, was in fact implementing a policy similar to the Ideal, in that he repeatedly took his design team to the plant to build prototype vehicles off the assembly line. His development project lasted longer than two years, and he believed that more than six months between builds were necessary to allow sufficient time for design engineers to address problems identified in the previous review. Although the engineering vice-president was not pleased with these plant-based builds, Matt was convinced that they would ultimately serve the ambitious project well.[2] He said, "I think it helps get at the right issues, the tougher problems to resolve" (Interview notes, MM2.1.2). He also found serendipitously that over the nearly two years in which three early builds took place, the design team's relationship with manufacturing and assembly was improving drastically, as manufacturing and assembly learned more about the new product and

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[2] At the conclusion of this research, Matt's project had not staged its DIB, so it is unknown whether the early prototype builds effectively prevented "late" alterations to design.

became more personally involved with its development. At the conclusion of one build that took place off the assembly line, plant personnel asked Matt if the next prototype construction could take place *on* the assembly line—that is, they were offering to give up resources for current production in order to learn more about producing the new product before its scheduled DIB. Matt considered this a significant turning point in the design-manufacturing relationship.

Despite anecdotal evidence of the promise of early prototype builds in one protracted project, it may not be advisable or desirable to undertake prototype construction early in development. Prototype builds at the plant may not be the most efficient form of review accessible to manufacturing and assembly, particularly early in development. They may be considered unnecessarily costly, in terms of hardware and plant resources and staff time, to obtain benefits of early problem identification. Moreover, prototype construction may not comprise the only form of review congruent with production personnel's practices. Taking a cue from Matt's words above, we can view the key to early interdepartmental reviews is getting at the tougher problems to resolve. Thus it is important to ask—and to ask repeatedly, as skills in the organization shift through time—what artifacts and actions stimulate joint expertise across multiple departments? What are appropriate expectations for "real" parts and components in the early and middle months of development?

For a hardware-oriented organization such as the Company, answering this question poses a challenge. If manufacturing and assembly insist on seeing only artifacts that resemble as nearly as possible the end product, then design engineers feel pressure to postpone reviews with manufacturing and assembly until the design is "done" and prototyped in hardware. But until manufacturing and assembly learn about the new product enough to convey to design engineers its impact on their work, the design cannot be considered "done," and the pattern of late changes

may continue. It is worth considering, then, what artifacts, actions, and locations, short of assembling "real" hardware at the plant, can be accessible to manufacturing and assembly. Alternatively, it is worthwhile to consider ways to reduce the gap between manufacturing and assembly's practical knowledge and the tools and applications customary in design engineering. There is a wide continuum of choice in most of the dimensions of interdepartmental review activities at the Company. It is not necessary that design engineering project managers make many of those decisions alone. Perhaps project managers in design engineering can work with manufacturing engineers to *design* reviews accessible to plant personnel relative to that point in development—that is, to choose jointly the review's location, artifacts, and actions, for any given time in the development cycle, considering the current state of design. While considering new methods for representing early stages of design to manufacturing and assembly may sound far-fetched, at one time prototype builds at the plant were also an innovation, one viewed by some as costly and imprudent, and yet they have come to be seen as fixed and necessary in the development cycle at the Company.

In implementing some version of the Ideal scenario, one must also consider unpleasant social dynamics related to early problem discovery. Comparison of actual and apparent work complete under the Ideal scenario warns that it can be unrewarding socially and professionally to engage in reviews that surface problems effectively early in the development cycle. If, after one year of development work, one were to compare the Apparent Work Complete of two projects whose histories resembled those displayed in Figure 4.32, then the one labeled Ideal certainly appears less than ideal. It is entirely possible that such a project, under managerial review 12 months before its scheduled launch, would be canceled, given its numerous problems and costly investments in early reviews for which it evidently is unprepared. The Current project, however,

which appears to have far fewer problems, would receive support to continue. Thus any intervention to alleviate late changes must account for these social dynamics and shape organizational expectations to encounter, and even welcome, rather unappealing early surges of problems and design changes.

Therefore achieving the Ideal pattern of design changes necessitates setting or re-setting expectations in at least two regards. First, the Company can consider what are "real" representations of new products to manufacturing and assembly staff at different points in the development cycle. Second, it can reconsider the notion that discovering problems early in development is indicative of future project failure. Too often early problem discovery is viewed primarily in terms of cost, while late problem correction is viewed primarily in terms of heroics (Repenning, Gonçalves, and Black, 2001). As Matt says of his own experiences with early prototype builds:

> People think that if you model enough and do enough analysis then the process will go smoothly. It's always ugly when you do a prototype build at the plant. It's an ugly process. I think setting expectations is part of it. If we could convince people that being ugly is not necessarily bad, we could improve communication. I tell people, "This [long before DIB] is the right time to be ugly.... It's better it sucks now than at FPE" (Interview notes, MM2.1.2).

Reconsidering timing and nature of reviews

The simulations shown in Section 4.5 suggest that the Ideal pattern of design changes concluding well before launch is possible when reviews accessible to manufacturing and assembly occur at a frequency to keep the stock of design engineering knowledge climbing. In the Current simulation, when the reviews accessible to manufacturing and assembly occur later, design engineering knowledge about the new product design plateaus between the time that most new engineering tasks have been completed and the first "realistic" review (see Figure 4.20).

In the Current scenario, a divergent conversation between design engineering and manufacturing and assembly—meaning, disagreement about the suitability of design, culminating in design changes—occurs with the DIB, when the organization desires convergent conversation, agreement that the new product design is good. With the benefit of simulation, we can see that design-changing conversation occurs when two conditions are satisfied simultaneously. The first condition is that neither department knows all there is to know about the new product (neither party is fully "invested" in its current understanding), as when the value of DE Knowledge about New Product Design is much less than 1, and the value of the stock M and A Knowledge about New Product Manufacturing is much less than 1. The second condition is that the departments' respective knowledge about new products is roughly balanced across the boundary; in other words, the ratio of design engineering knowledge to manufacturing and assembly knowledge is near 1. Figures 4.33a and 4.33b juxtapose the ratio of knowledge across the boundary with the rate of Identifying Problems, the result of divergent conversation across the design-manufacturing boundary.

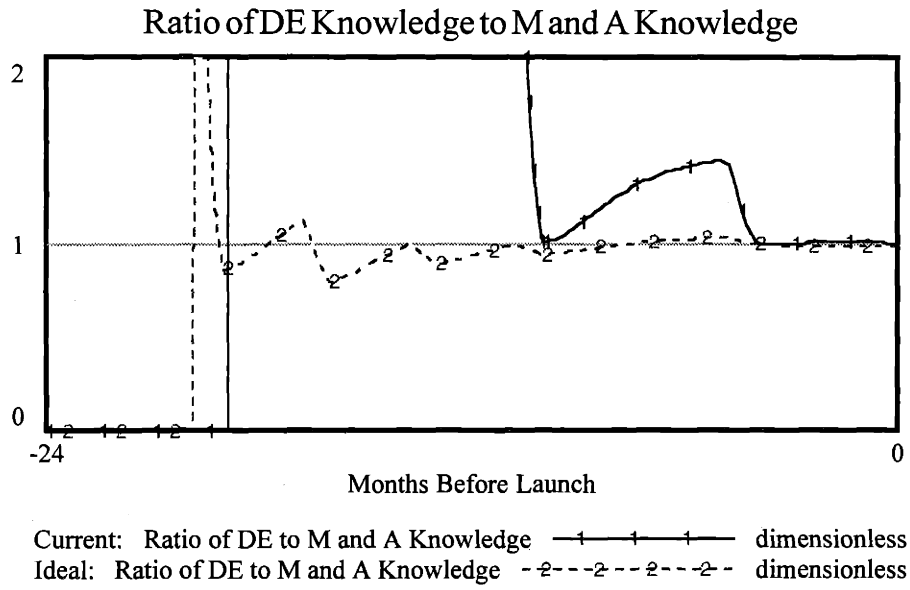


Figure 4.33a: The ratio of Design Engineering Knowledge to Manufacturing And Assembly Knowledge

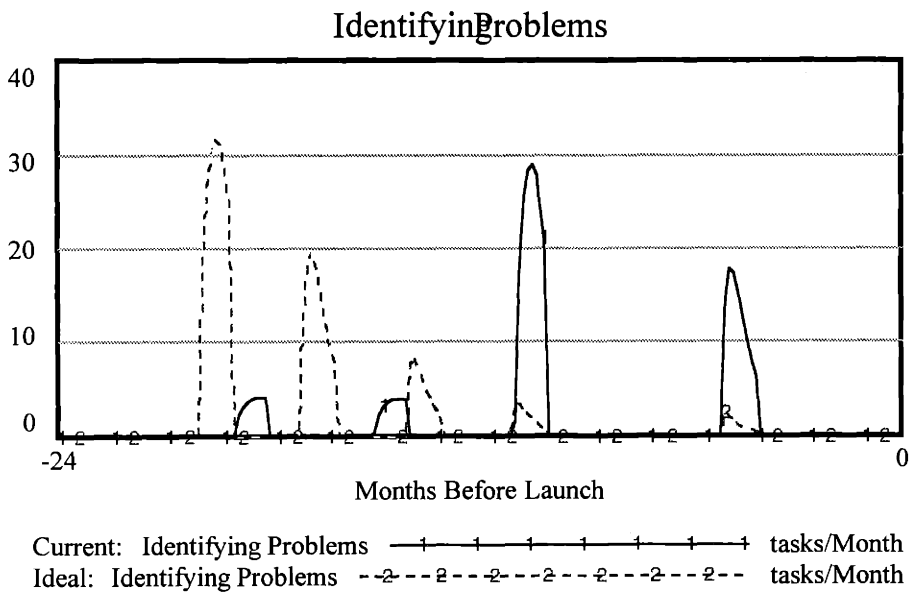


Figure 4.33b: Identifying Problems in Current and Ideal Scenarios

When design engineers' knowledge of new products greatly exceeds manufacturing and assembly's knowledge of new products, there is no divergent conversation—in fact, there is almost no interdepartmental conversation, as manufacturing and assembly have not learned enough about the new products from reviews which, if they occur, are staged in the language and tools of design. The divergent conversation, stimulated by reviews accessible to manufacturing and assembly and leading to design changes, helps increase both departments' knowledge. In the simulations, when both departments' knowledge stocks approach 1, design changes conclude because no more latent problems are being discovered, since the problems have already been identified and resolved. It seems clear both from model analysis and empirical observation that divergent conversation, precipitated by plant personnel's significant increase in knowledge about the new product, will occur at some point during development. The timing of reviews accessible to manufacturing and assembly simply accelerates or postpones it. If problem identification and resolution is desired early in development, then reviews that rebalance amounts of knowledge across the design-manufacturing boundary can encourage the divergent conversations that lead to problem identification.

Since design engineering's work must always precede the new product work of manufacturing and assembly, design engineering will always accumulate knowledge of the new product before manufacturing and assembly. It is impossible to prevent imbalances in knowledge across the design-manufacturing boundary from occurring. But it is not necessary that imbalances in knowledge persevere until the DIB and FPE prototype builds at the plant. Reviews can serve as occasions for rebalancing knowledge about new product work across the boundary. This is possible if review activities are shaped to compensate for the party who knows less about the interdependent work at the time the review occurs. If knowledge is distributed

among locations, artifacts, and actions as well as what is retained in mind, then we might assert that participants' knowledge of the work at hand may rise or drop contingent on the review's congruence with participants' practices (I did not conceptualize the model in this way; I assume that knowledge, once gained, is not lost). The ratio of knowledge between design engineering and manufacturing and assembly can thus inform the desired nature of a review at a particular time during development. Designing the locations, artifacts, and actions of cross-boundary interactions to favor the practices of manufacturing and assembly, when design engineers' knowledge of new product work has outpaced plant personnel's, may effectively redistribute organizational expertise to reduce the lag between accumulations of knowledge on either side of the boundary. In other words, it may be possible to redress imbalances in expertise across the boundary and make the less experienced party "more knowledgeable" with the thoughtful design of interdepartmental reviews based on an understanding of whose knowledge is greater at a particular point. In this way reviews shaped to compensate for imbalances in relative expertise to wield the tools used in interdepartmental conversations can support collaborative interactions in which each party learns more about the interdependent work.

4.6 Discussion of qualitative and model analyses

Analyses of this field study of interdepartmental reviews during new product development suggest that two mismatches take place at the Company, inhibiting collaborative interactions. First, qualitative analyses of three types of reviews point to a commonly occurring mismatch between dimensions of a review, such as its artifacts, actions, and location, and the tools, applications, and places customary used by manufacturing and assembly participants in

their work. This results in little participation by plant personnel. Reviews near the end of the development cycle, during which full-scale prototypes are built at the plant, are the first reviews salient and engaging to manufacturing and assembly. Identification of latent problems during these reviews lead to design alterations late in the development cycle, creating a persistent, undesirable pattern in the Company's product development. Second, simulations from a model grounded in the field data suggest that sufficiently early reviews that engage plant personnel in identifying problems can increase the knowledge of both design and manufacturing early in the development cycle and help conclude design changes well before launch. Simulation analyses indicate that imbalance in amounts of knowledge about new product work across the design-manufacturing boundary can persevere through most of the development cycle, leading to "late changes," unless deliberate steps are taken to stage reviews highly accessible to manufacturing and assembly early in the development process.

Accessible to whom? or, transforming knowledge through effective representation

We can consider that accumulations of new product knowledge distributed in the Company are linked through interdepartmental reviews and efforts to resolve new product problems identified by the reviews. Design engineering knowledge informs the cross-departmental review, at which manufacturing and assembly staff learn about the new product. As plant personnel come to know the product under development, they participate more actively in interdepartmental reviews, and they identify latent problems in the effort. As design engineers draw on their knowledge to resolve problems, they increase their own understanding of the new product design.

Qualitative analyses suggest that these interdepartmental learning dynamics hinge on effective representation of the new product by design engineers to manufacturing and assembly staff. Therefore a critical issue for bringing distributed expertise to bear becomes identifying the kinds of interdepartmental interactions appropriate to the participants invited, the purpose of the review, and the point in the development cycle at which the interaction takes place (see Figure 4.34). Ideally, an organization will develop jointly accessible interactions in which all participants can increase their understanding of the work at hand. Characteristics of a robust cross-boundary practice (Carlile, 1997, 2002a) are embodied in the artifacts, actions, and location. When these aspects of the interaction are aligned with the work practices familiar to participants, then each party can manipulate the artifacts through actions using resources at that location, thereby increasing his respective knowledge of the work at hand (as depicted by smaller feedback loops to design engineering knowledge and manufacturing and assembly knowledge).

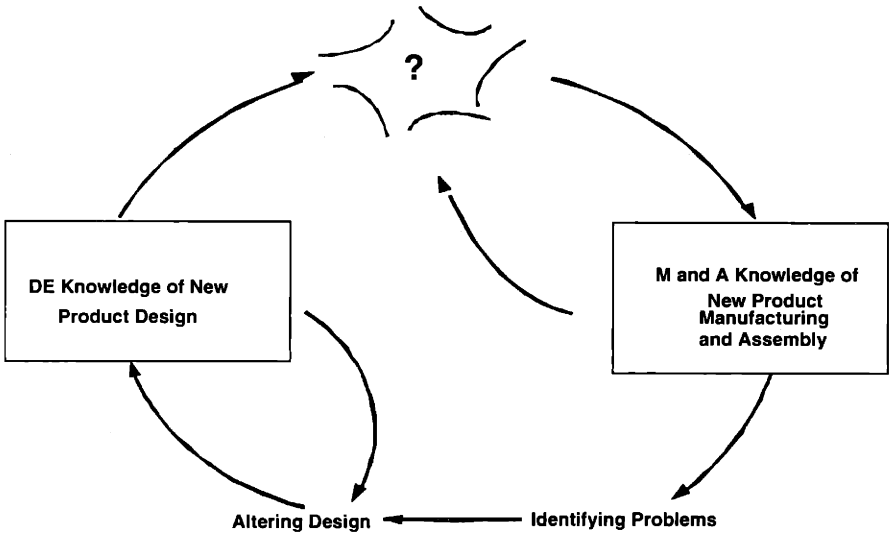


Figure 4.34: Links between new product expertise

In the model structure described in Section 4.4, I propose that reviews accessible to manufacturing and assembly are more effective at identifying latent problems in the new product work-to-date. The term "accessibility" merits exploration. On its face, it means "capable of being used or seen; capable of being understood or appreciated" (*Webster's Ninth New Collegiate Dictionary*), and I have suggested that when the artifacts, actions, and location of a review resemble participants' practices, they are accessible to those participants. It is crucial to note that accessibility is always relative to participants' skill-set. If the manufacturing and assembly crew is well-versed in CAD/CAM, for example, then an accessible location is not necessarily the plant but rather a facility equipped with CAD/CAM displays. For an organization that makes products such as semiconductor chips, products so small that holding the finished good provides significantly less information than CAD images, a "concrete" artifact is not functioning hardware but something that permits participants to manipulate a representation of the work-to-date.

Given that accessibility depends on congruence between practical use of the artifacts, actions, and location of a cross-boundary interaction and the practices of its participants, we can reconsider technologies and procedures that promise to reduce dramatically the time between designing new products, reviewing work-to-date, identifying problems, and addressing problems. "Rapid prototyping," for example, can be effective to the extent that the prototype renders an artifact appropriate to the skill-set of the reviewer. In software development, demonstrating a prototype to an expected user (who presumably possesses skills not greater nor less than other anticipated users) may prove valuable, as long as the user can make her concerns about the proposed product understandable to developers. In industries where prototyping technologies are more costly than software duplication and display, attributes of artifacts, actions, and locations

proposed for a review might be considered in light of their suitability to the skill-sets of participants and the intent of the review.

Solid modeling provided by CAD was originally hailed in product development communities as a tool that could close the "great divide" between design and manufacturing (Adler, 1995). Display and rotation of three-dimensional drawings does indeed prove useful in conveying general ideas about product design to manufacturing. But unless people on both sides of the design-manufacturing boundary are skilled in CAD technology, a divide between design and manufacturing and assembly remains, reinforced by one side's ability to manipulate the technology while the other cannot. In that case, as at the Company studied, where plants had limited access to CAD, manufacturing and assembly participants become spectators of the display. Although the review artifact appears in three dimensions, whether the product can be manufactured with existing assembly line configurations or whether its proposed dimensions allow for tolerances that can be met effectively 200 times a day remains unknown.

If an organization seeks to improve cross-boundary interactions, it does not necessarily need to design the review for participants' existing skill-sets. An alternative approach is to train participants with skills needed to exercise the desired artifacts, actions, and locations. Although providing participants with new skills may require more planning, investment, and a longer time horizon than adapting aspects of a review for current expertise, in the long term it could prove more effective than, say, interrupting current manufacturing operations repeatedly to assemble prototype products. It probably bears repeating, as suggested by simulations in Section 4.5, that even organizationally expensive reviews that identify problems may be cost effective if they prevent even costlier corrections late in development or after the product has entered the customer's domain.

It would be a mistake to conclude from this discussion that the Company, or any organization, should hold reviews that include only certain kinds of artifacts, actions, and locations. Much more challenging is to design processes for creating joint accessibility across a boundary, rather than accessible objects or settings. This distinction is important for at least two reasons. First and most obvious, organizations evolve through time, and representations appropriate to a boundary-crossing interaction will grow obsolete as facilities, technologies, and participant skill-sets change. Second, each embodied aspect of a cross-boundary interaction represents some elements of participants' practices and not others. What remains unrepresented is not necessarily unimportant; therefore processes for bringing into discussion new representations of knowledge, however embodied, can prove valuable.

When viewed in light of the knowledge-sharing framework distinguishing among knowledge transfer, translation, and transformation (Carlile, 2002b), the early project reviews and many model-year reviews at the Company appear to assume that the purpose of the joint activity is to *transfer* knowledge. That is, the artifacts, actions, and location of these reviews seem predicated on the idea that design engineering speaks to audiences who share design engineering's syntax. When the audience is indeed composed of design engineers, displaying engineering drawings works well in conveying information and identifying possible problems. When non-design-engineering employees attend, however, presenters perceive non-participation, and latent problems (problems related to manufacturing but often resolved through alterations to design) in the new product remain undiscovered. Since, in the reviews observed, design engineers do not attempt to tell manufacturing and assembly staff how to tool for new products, there seems to be no effort to *translate* semantics from design engineering's often two-

dimensional, static view of a new product to departments specializing in three-dimensional aspects of product development and the processes to produce them multiple times a day.

While many new technologies and product development methods promise to reduce the design-manufacturing interface to a simple transfer or translation of information, the perseverance of problems with cross-functional integration suggests that the boundary is "pragmatic," to use Carlile's (2002a, 2002b) term. In this case we look to interdepartmental interactions to *transform* what both manufacturing and assembly and design engineering know about new product work. While the system dynamics modeling employed in this study represents only the *level* of knowledge accumulated through cross-boundary activities, theorizing must acknowledge that the *substance* of the exchange itself can change depending on the artifacts, actions, and locations used and their accessibility to participants on either side of the boundary. In other words, accessibility of joint activities can change not only how much is learned but also the nature of the knowledge gained; that is, knowledge transformation often requires people to relinquish previous, hard-won knowledge in light of new understandings. To transform each party's knowledge, the interaction must allow both departments to represent—and legimate (Suchman, 1995)—what they know and how their understanding of the new product at hand affects the work of the others, and to manipulate aspects of the interaction to express their knowledge. At the Company, the prototype builds, whether method-mandated or platform-instigated, effectively transformed manufacturing and assembly's understanding of the new product. This new knowledge of the product under development allowed them to identify problems. Newly identified problems, in turn, transformed design engineering's understanding of the consequences of product design decisions represented in the product prototype. The pivot

point for knowledge transformation rests on making cross-boundary events effective for joint accumulation of knowledge of the interdependent work.

Timing reviews to rebalance expertise across the boundary

In the Company studied, under the current product development practices, divergent conversations take place about the suitability of the product design at a time when convergent conversations are desired by nearly everyone in the organization. The simulation analyses above suggest that this occurs because assembling a full prototype vehicle at the Design Intent Build is often the first cross-boundary interaction that is truly accessible to manufacturing and assembly. Of course, given the project overload of most product development organizations (Wheelwright and Clark, 1992; Smith and Reinertsen, 1998) and the persistent dynamics that can result from work-resource imbalance (Repenning, Goncalves, and Black, 2001), it is possible that the method-mandated prototype build is the soonest point at which design engineers know enough to obtain functioning prototype hardware. Since almost every organization struggles to allocate scare resources among a variety of activities, choosing how and when to invest in interdepartmental reviews becomes an even more important issue than if we assume, as the model did, engineering resources are adequate. A well-structured and well-timed review—one whose attributes are well-matched with participants' skills—that identifies latent problems and aids in their early resolution can alleviate the fire-fighting dynamic that demands more resources in the weeks immediately preceding launch. When should design engineering initiate reviews accessible to other departments, so that reviews are most useful, yielding a high payoff in problems solved for the effort invested to stage the reviews?

Clearly it is impossible to assess directly how rapidly a department's knowledge is changing. Nevertheless it is worthwhile to consider how design engineering can know, as it is doing new product work, when to hold reviews with manufacturing and assembly (and other departments) and how to shape those reviews to obtain the active engagement and thorough identification of problems desired. When one is in the middle of development, how does one determine when to hold an intensive interdepartmental review? One approach relies on carefully documenting all problems, identified and resolved, associated with a project. After each interdepartmental review, the project manager can assess whether new problems are being identified, which suggests that manufacturing and assembly are learning more about the new product work, and whether old problems are reemerging, which indicates that design engineers are not learning from previously identified problems.

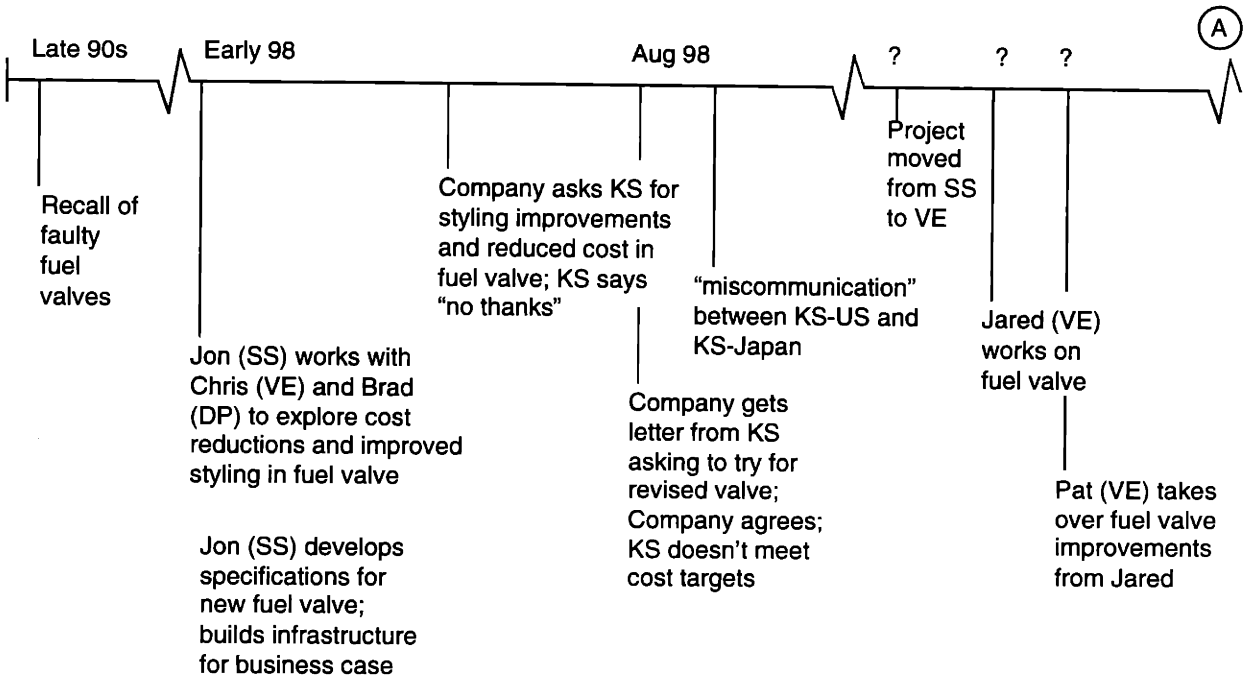
Another approach identifies at the start of a project a rough target for cumulative problems solved, estimated by looking at previous projects' ratio of cumulative problems solved by launch to the number of developmental part numbers established at project initiation. (A developmental part number is established for each part to be created or modified in the course of development. This reduces confusion between parts under development and parts currently in production.) At the Company studied, the ratio of a model year's cumulative problems solved by launch to developmental parts established 24 months before the model-year's launch was surprisingly consistent year over year. With such a heuristic, then, at the start of a new project, a project manager can multiply the estimated number of new or changed parts by the ratio of problems solved to developmental parts, offering a target or benchmark for problems to identify and resolve. If midway through development the number of problems logged is far below the target, then more cross-boundary activities may be in order. Moreover, making a project team

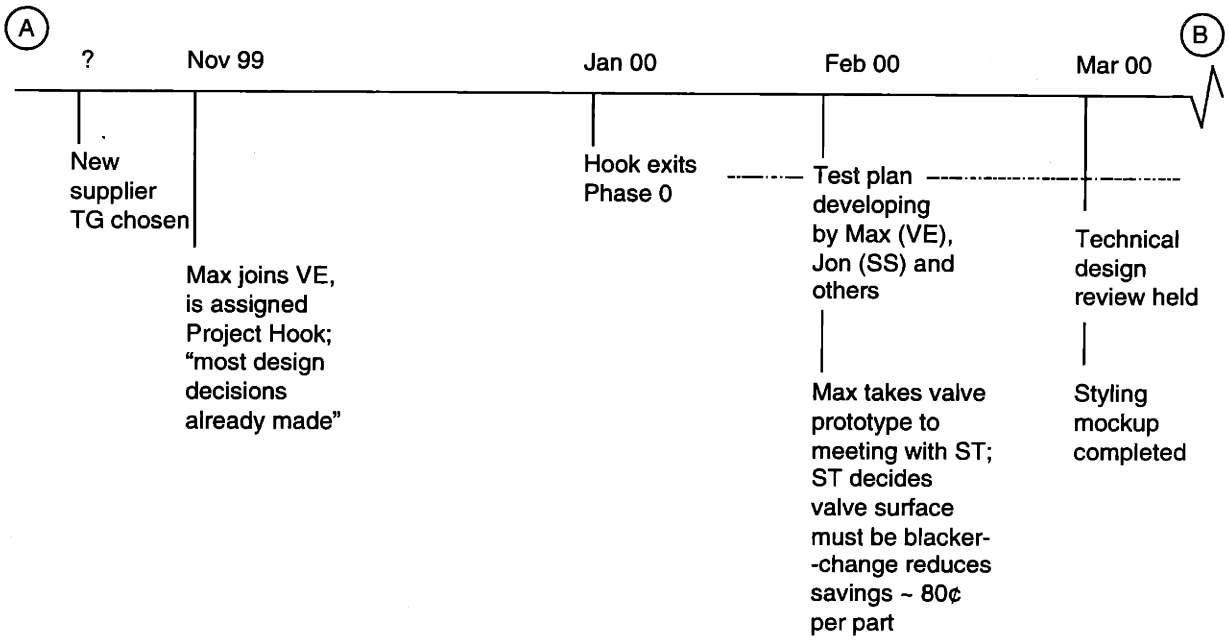
aware of such a target might go a long way toward casting early problem identification in a positive light and alleviating unpleasant social dynamics within design engineering that may accompany early problem identification.

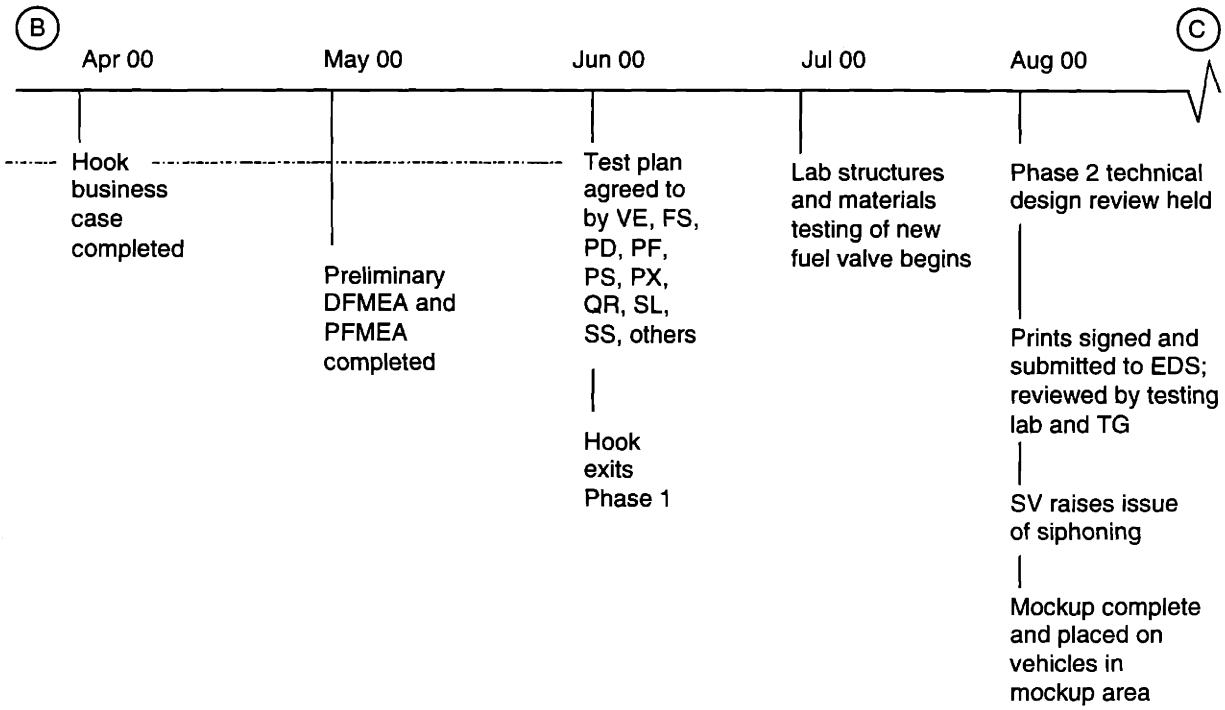
Closing Thoughts

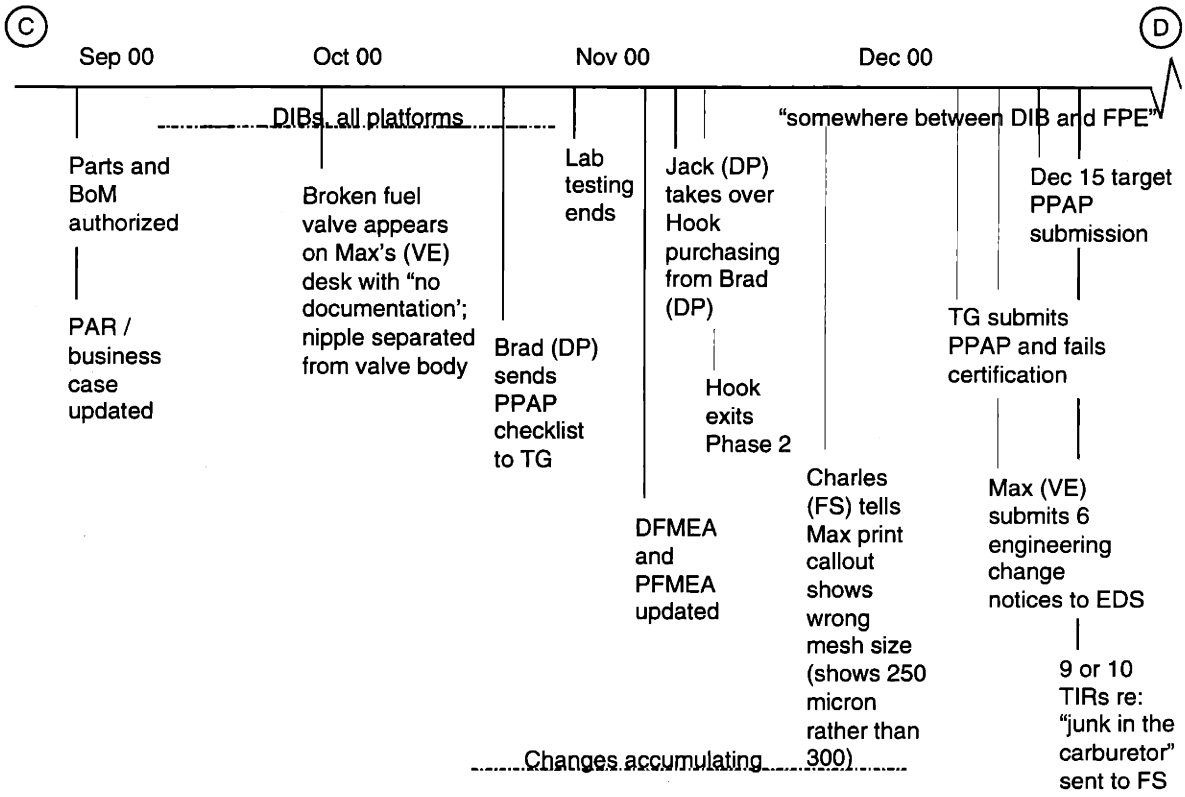
This field study provided the opportunity to explore and theorize about the micro-practices of interdepartmental interactions and their role in a more comprehensive framework of knowing and doing work. It examined the role of timing of joint activities in the flow of work and how interdepartmental activities well-timed and well-matched to participants' abilities may rebalance expertise distributed across organizational boundaries and keep people involved and productive in interdependent work. While this research does not presume to provide an answer to the problem of integrating disparate expertise in new product development activities, it does suggest a better question. What actions, artifacts, locations, and timing can create and sustain capability for joint accessibility to new product review activities among departments specializing in different kinds of expertise? Attending to these aspects of cross-boundary interactions may be more unsettling than relying on stage-gates or other prescriptive practices, but it can yield understanding of the underlying mechanisms, both physical and social, that make such practices work.

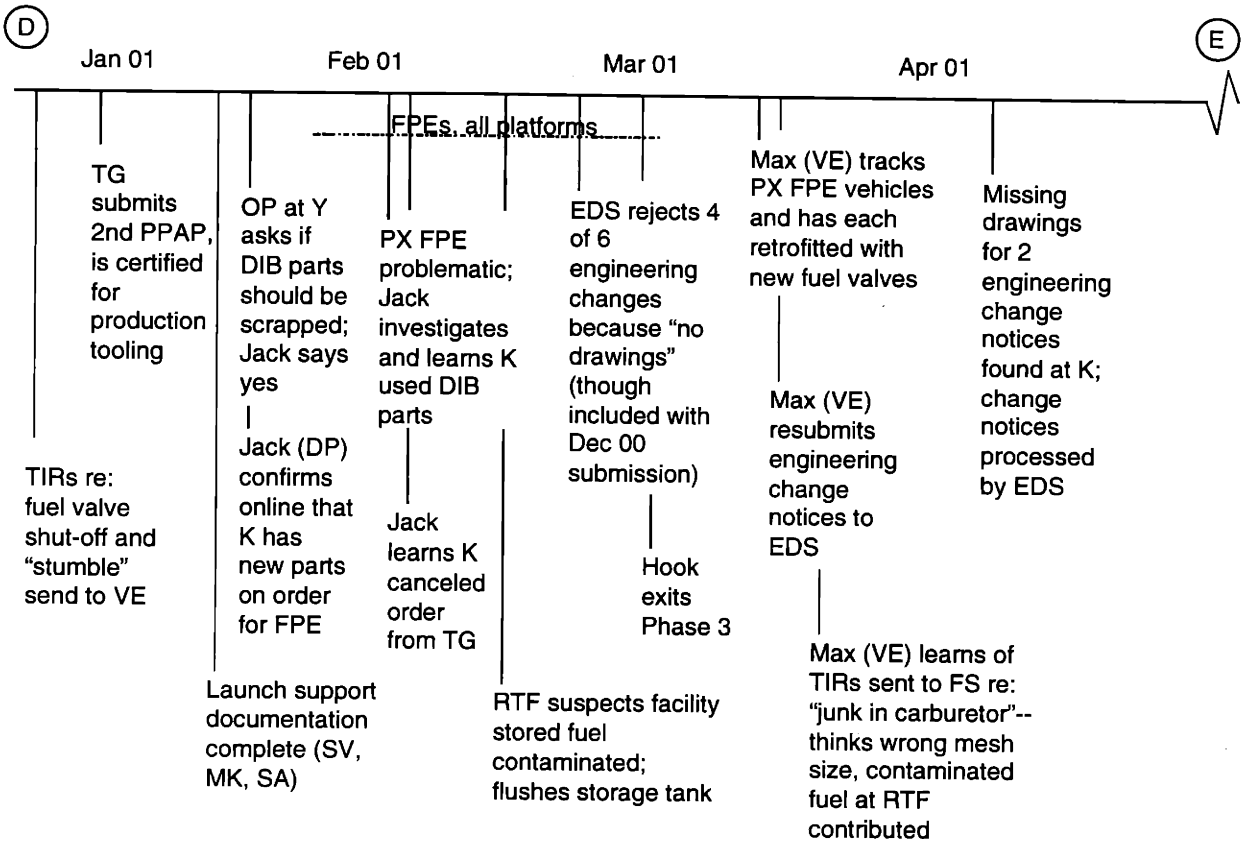
Appendix A to Chapter 4: Timeline for Project Hook




A
?
Nov 99
Jan 00
Feb 00
Mar 00
B
New supplier TG chosen
Max joins VE, is assigned Project Hook; "most design decisions already made"
Hook exits Phase 0
Test plan developing by Max (VE), Jon (SS) and others
Max takes valve prototype to meeting with ST; ST decides valve surface must be blacker--change reduces savings ~ 80¢ per part
Technical design review held
Styling mockup completed


B
C
Apr 00
May 00
Jun 00
Jul 00
Aug 00
Hook business case completed
Preliminary DFMEA and PFMEA completed
Test plan agreed to by VE, FS, PD, PF, PS, PX, QR, SL, SS, others
Hook exits Phase 1
Lab structures and materials testing of new fuel valve begins
Phase 2 technical design review held
Prints signed and submitted to EDS; reviewed by testing lab and TG
SV raises issue of siphoning
Mockup complete and placed on vehicles in mockup area


C
D
Sep 00
Oct 00
Nov 00
Dec 00
DIBs, all platforms
"somewhere between DIB and FPE"
Parts and BoM authorized
PAR / business case updated
Broken fuel valve appears on Max's (VE) desk with "no documentation'; nipple separated from valve body
Brad (DP) sends PPAP checklist to TG
Lab testing ends
Jack (DP) takes over Hook purchasing from Brad (DP)
Hook exits Phase 2
DFMEA and PFMEA updated
Charles (FS) tells Max print callout shows wrong mesh size (shows 250 micron rather than 300)
TG submits PPAP and fails certification
Max (VE) submits 6 engineering change notices to EDS
Dec 15 target PPAP submission
9 or 10 TIRs re: "junk in the carburetor" sent to FS
Changes accumulating


D
Jan 01
Feb 01
Mar 01
Apr 01
E
FPEs, all platforms
TG submits 2nd PPAP, is certified for production tooling
OP at Y asks if DIB parts should be scrapped; Jack says yes
PX FPE problematic; Jack investigates and learns K used DIB parts
EDS rejects 4 of 6 engineering changes because "no drawings" (though included with Dec 00 submission)
Max (VE) tracks PX FPE vehicles and has each retrofitted with new fuel valves
Missing drawings for 2 engineering change notices found at K; change notices processed by EDS
TIRs re: fuel valve shut-off and "stumble" send to VE
Jack (DP) confirms online that K has new parts on order for FPE
Jack learns K canceled order from TG
Hook exits Phase 3
Max (VE) resubmits engineering change notices to EDS
Launch support documentation complete (SV, MK, SA)
RTF suspects facility stored fuel contaminated; flushes storage tank
Max (VE) learns of TIRs sent to FS re: "junk in carburetor"-- thinks wrong mesh size, contaminated fuel at RTF contributed

(E)

May 01 | Jun 01 | Jul 01 | Aug 01

New fuel valve launches on more than 20 models on 4 platforms; estimated savings $7+per vehicle, totaling $1 million annually

Departmental Abbreviations:

DP	Developmental Purchasing
EDS	Electronic Data Services
FS	Fuel Systems
K	Plant K
MK	Marketing
PD	Platform D
PF	Platform F
PS	Platform S
PX	Platform X
OP	Operations Purchasing
QR	Quality and Reliability
SA	Sales
SL	Structures Lab
SS	Styled Surfaces
ST	Styling
SV	Service
T	Testing (place unknown)
RTF	Road-Test Facility
VE	Value Engineering
Y	Plant Y

Other Abbreviations:

DFMEA	Design Failure Mode Engineering Analysis
DIB	Design Intent Build
FPE	First Production Event
KS	Supplier of fuel valves until 2001
PFMEA	Process Failure Mode Engineering Analysis
PPAP	Purchasing's certification process for supplier's production tooling
TG	Supplier of fuel valves beginning in 2001
TIR	Test Incident Report (produced by RTF)

Appendix B to Chapter 4: Narrative summary of Project Hook

Why was Hook a project, anyway?

One could argue that Hook should never have been termed a "new product development" project. It was primarily a supplier change for a fuel valve used in the Company's carbureted engines. Why would a supplier change merit the organizational overhead of a "project," with formal leadership and the coordination costs of design reviews and project reviews, integration into the new model year's prototype builds, and significant project and process documentation? There are two primary reasons. First, because design engineering resources are scarce, creating the organizational focus to achieve in a timely manner the estimated savings (more than $1 million annually) in parts used across four platforms meant that someone—with a deadline—needed to spearhead the effort. Second, the Company wanted to ensure that the current supplier's parts would not be used in service/replacement applications, and a new product's new part numbers would create a desirable discontinuity that would purge part numbers for components provided by the current supplier from bills of materials, parts catalogs, and service documentation.

In 1996 a recall of faulty fuel valves from the current supplier, KS, triggered the Company's initial search for a new supplier. Early investigation of TG, second (behind KS) in the fuel valve market, revealed a reasonable candidate and a significant potential for cost savings. But as Jon, a powertrain engineer said, "If you're a supplier to [the Company], you're in the catbird seat." In other words, the Company tends to keep its current suppliers, rather than switch rapidly among competitors. Even though the Company didn't pursue TG right away, and

KS supplied adequate fuel valves for several years after the recall, the potential cost savings remained an opportunity. The impetus of a new product development project lent focus to insisting that the current supplier perform to new specifications at reduced costs or relinquish its position to a competitor.

At the prospect of a supplier change, the Service department, responsible for maintaining parts at dealers used for repair, requested that the new fuel valve be treated as a model-year change, rather than a "running change" to an existing part, so that a new part number for the new valve would distinguish it unequivocably from any stock of service parts provided by the current supplier. A model-year change provides the primary mechanism for effecting changes to part numbers and to catalog and service manuals. According to the Company's Concurrent Product and Process Delivery Methodology, a model-year change takes place only through a new product development project, which entails substantial documentation in keeping with the Company's ISO 9000-certified processes.

Furthermore, despite growing awareness of the benefits of commonizing parts, the fuel valve is among very few parts in use on all four of the platforms existing in the late 90s. Variations in fuel tank styles across 20 to 30 models in the four platforms presented challenges for creating an efficient and effective test plan to prove out the valve's safety for all configurations. Coordinating across the platforms was made easier by establishing a project leader focused on implementing the change in a particular model year. In addition, since the fuel valve is literally a small part, not figuring prominently in the "look" of the vehicle, the visibility of a new product project provided some organizational legitimacy to attending to a visually inconsequential change.

A note about the function of the fuel valve

The fuel valve is used in non-fuel-injected engines to stop the flow of gasoline from the fuel tank to the carburetor when the engine is not operating. When installed correctly, the valve creates a vacuum between it and the manifold. When the engine is running, the vacuum from the manifold evacuates the fuel valve chamber, pulling on the diaphragm and "plug," which allows the fuel to flow freely by gravity (see Figure A1.1). Without the fuel valve, the flow of fuel could continue after the engine is turned off, leading to overflow and fuel spillage.

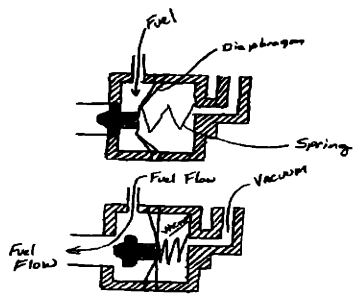


Figure 4.B.1: The function of the fuel valve

Redundantly, the fuel valve used in this Company's vehicles also has a manual shut-off. Therefore the switch on top of the valve shows three positions: "off" (no fuel passes from the tank to the carburetor); "on" (the valve operates normally, drawing fuel from the tank until only a few gallons remain in the tank); and "reserve" (the valve operates normally, draining the tank completely). The "reserve" feature allows the driver of the vehicle to drive with the valve in the "on" position until the fuel gauge registers as "empty," and then to switch the valve to "reserve" and have sufficient fuel to drive for a limited time, presumably long enough to obtain more fuel.

The entire valve assembly is about six inches long, with a little more than an inch of that visible on the fuel tank. The part of the valve most visible to the user is a chrome switch with a pointed "head" (to indicate the position selected) and elongated tail. Underneath the switch and on the sides of the valve protruding from the fuel tank is the black metal mount, a little more than an inch cubed.

Early work on the fuel valve—"pre-project" days

In early 1998, a few months after Jon started with the Company, his group was reorganized and Jon was placed in the Styled Surfaces COE (Center of Expertise). He was asked to begin working on cost reductions and improved styling to the fuel valve used in all carbureted engines, which was still supplied by KS, even after the 1996 recall. Jon worked on improvements to the fuel valve in conjunction with Value Engineering, a small group focused on cost reduction efforts in product development, but was then directed to work on a large new product effort to develop an alternative engine cooling system. Most of his energies were necessarily devoted to the larger, more demanding project. Project Hook was "on the shelf," Jon said. "I had developed a good relationship with the Value Engineering group. I talked with Chris [the manager of Value Engineering] and Brad [a member of Developmental Purchasing] about cost reduction and improved styling—they loved the prototype in chrome." With Chris and Brad, Jon developed specifications for a new valve and built a preliminary business case for the effort. Specifically the Company desired a newly stylized diverter lever (switch) with a detent (a user-satisfying click when the lever is moved from position to position) and a per-part cost reduction of about $5. At the time, it was regarded as a "running change" to a current part, not a new product effort.

In mid-1998, the Company invited its current supplier of the fuel valve, KS, to provide styling improvements and reduced cost. KS declined. At that point the Company felt justified in evaluating alternative providers. But because Jon worked on the fuel valve effort only secondarily to his main development tasks, progress on the new fuel valve was sporadic and slow.

During early 1999, Chris proposed that the new fuel valve effort become a project in its own right, to be spearheaded by a member of his group, Value Engineering. Most of the projects within Value Engineering are driven by cost savings (MZ.1.1), and Chris reasoned that the per-part reduction in cost promised sufficient savings to the Company to warrant its receiving significant organizational focus.

A note about the product development method

The Company's product development efforts are guided by the Concurrent Product and Process Delivery Methodology (CPPDM), first documented in 1994, when the program management office for product development was first created, and revised four times since. It structures development into five phases, numbered 0 through 4, and stipulates activities and documentation that must be completed within each phase. During the first two phases, the Product Planning Committee, a cross-departmental (mostly Marketing and Engineering) managerial board reviews the project progress and renders decisions. During phases 2 through 4, the Quality, Reliability Leadership group, a cross-departmental (mostly Engineering and Manufacturing) managerial board, bears responsibility for monitoring project progress and rendering decisions as needed.

Phase 0, the "idea" phase, begins with describing the idea and ends with a presentation of a business case, with quality, cost, and timing targets estimated, along with required human and capital resources needed to bring the idea to life. Theoretically, a project should not be scheduled to launch in a particular model year until it has exited Phase 0. In reality, however, many projects are scheduled to launch before their Phase 0 begins, or Phase 0 is simply omitted (notes from launch assessment MY99).

Phase 1 consists primarily of engaging stakeholders across the organization to provide input to development plans and assess risk. For these plans and risk assessments to be appropriately specific, a certain amount of new product design, review, and testing must occur during this phase.

During Phase 2 the bulk of design, development, and vehicle integration takes place. The project leader should document that the design output achieves the appropriate specifications, as well as complete quality control, homologation (regulatory emission requirements), service and plans and configurations. This phase ends with the Design Intent Build, a prototype vehicle build on the assembly line in the early fall that represents the end design ("design intent") of all new product projects to launch the following summer. By the time the Design Intent Build (DIB) takes place, all new parts for a project should be "authorized," or officially documented by the Company's Electronic Data Services group, which maintains the integrity of the CAD repository of engineering drawings for parts in use.

Phase 3 focuses on preparing equipment and tooling and manufacturing processes. It concludes with the First Production Event (FPE), a prototype vehicle build on the assembly line in January or February that represents the manufacturing processes to be in production when the

new model year launches the following July. While DIB vehicles may include prototyped parts, FPE vehicles should include only production-tooled parts.

Phase 4 validates the production system and manufacturing training and documents that all support documentation (for marketing, sales, and service) is complete and accurate. The project terminates with the project leader's preparing a "make good report" on how the end product measured against its quality, cost, and timing targets.

Hook's first months as a project

Although Jon was willing to remain involved with Hook, the Styled Surfaces COE (Center of Expertise) relinquished the effort, and Jared in Value Engineering took over leading conversations with Brad in Development Purchasing to evaluate TG, the alternative supplier identified as a strong player in the fuel valve market. When Jared then moved to a new position in a different group, Pat in Value Engineering for a short time became responsible for the fuel valve effort. Since both Jared and Pat were juggling other projects with more imminent launch dates, however, Hook didn't received concerted effort. In November 1999 Max joined Value Engineering and was given responsibility for the project, as Chris sought to distribute his group's workload equitably. By the time Max took the lead on Hook, Jon, whose work had by now shifted to powertrain development, had provided most of the continuity to this effort to obtain a newly designed, reduced-cost fuel valve for carbureted engines.

Making project progress

In November 1999 Max was satisfied that most of the design decisions for the new fuel valve had already been made and adequately documented in developmental drawings and in lists of specifications. Therefore he viewed his first task as documenting the work completed to date

in keeping with the Company's product development method (CPPDM). He devoted his efforts to writing up the estimated financial benefits based on TG's estimates of per-part costs and constructing the preliminary business case for Hook. By January 2000, he had provided the program management office evidence that Hook had exited Phase 0, the concept identification phase. Early estimates suggested that the Company could save more than $1 million a year in part costs by switching to TG. TG agreed to provide the styling changes specified and to create a small vent near the top of the fuel filter to prevent a sporadically documented problem called "siphoning." TG also proposed upgrading the seals in the valve to a more chemically resistant material called Viton, which could increase the longevity of the fuel valve in the face of additive-rich fuels increasingly in use.

In February 2000 Max took a hardware prototype of the prospective supplier's fuel valve to the Styling department for a routine approval check. Styling, which bears responsibility for the "look and feel" of the vehicles produced by the Company, had seen and approved previous prototypes, Max said. This time, however, it suggested that the surface of the valve under the switch, a piece of hardware about the size of a 50-cent-piece, should be a "blacker black." Rather than leaving the surface with an anodized finish, which was a greenish-black color, Styling suggested that the surface be painted. Having the supplier paint the part was not problematic, Max said; it simply reduced the savings per part by about $0.80. "It's not really a big deal," he said. "The question just boils down to, 'Is this one about $130,000 a year blacker than this one?'" (MZ.11.1; dollar amount based on projected vehicle volumes).

In February Max also began refining the preliminary test plan he had inherited from Jon's work with Jared and Pat to prove out the new fuel valve. He met with representatives from TG, engineers in the four platform groups whose models use carbureted engines, and engineers in the

Styled Surfaces COE, which "owns," or bears primary responsibility for keeping prints accurate, the fuel tank and the fuel valve. Because the vehicles using the carbureted fuel valve exhibit 16 fuel tank configurations used on more than 20 models, Max sought to create an efficient test plan to validate the valve's safety for all configurations—without performing extensive materials, structural, and road testing on each one of the variations. Test plan development proceeded slowly.

> There was some difficulties in developing a proper test plan. ...[I]t's my understanding that there's not a lot of projects here that go entirely across platforms like this. And when you do have a project that goes across all these platforms, plus you have COEs involved, and...representatives from service parts and everything else, there's a lot of people with a lot of input. And getting them all to agree, or getting them even to *give their input* is challenging. That is one of the reasons—there was a time in the project where it wasn't particularly progressing very quickly, and that was why. (MZ.3.5 – 4.1)

Because Max was new to the Value Engineering group, he had first to learn what was expected of him and how to accomplish what was expected of him. "The system was just entirely different to begin with," he said (MZ.4.2). Max had previously been an engineer in the Parts and Accessories (P&A) department. Since P&A doesn't use the product development methodology prescribed by the program management office, and it doesn't work with a platform / COE matrix organization, Max needed to learn a new work process and a new organizational set-up, as well as become familiar with new people and what expertise they possessed. He said, "So it was a problem with not only asking the questions and getting people to answer the questions, but even finding who the right people to ask the questions *to* was difficult" (MZ.4.2). He thus proceeded organizationally by trial and error.

> In some cases it was really just, you know, essentially just tracking them down. And you ask a person, and they're the wrong person to ask, but they direct you to the next person, and you ask that person. And maybe they're the correct person, or they direct you to the next person (MZ.4.3).

As Max learned who knew what, he found that questions about how to test the fuel valve didn't have obvious answers. For example, "There was some vibrational testing that we were considering doing, wondering if it was necessary [and]...if it is necessary, what are your criteria for it.... It's not necessarily a 'yes or no' question." Suggestions ranged from testing all potential configurations in order to obtain a complete vibrational profile to testing only samples from the two platforms considered "likely [to] have the worst engine input" (MZ.4.4). Furthermore, Max found people "hesitant" to answer the questions he raised.

> I think that [hesitancy] stems from just the simple fact that this is a small thing on everybody's radar, so to get somebody to sit down and spend a lot of time thinking about "how do you want this done?" or "what do you think is an appropriate way to do this?"—to get them to sit there and actually think about it is kind of a difficult thing, when they have a million other things going on (MZ.4.5).

Max found that meetings weren't particularly effective in obtaining the information he needed. "I got very, very poor turn-out" (MZ.5.1). In March 2000 he held a technical design review that received limited participation, with three (not counting Max) of the 9 invited people showing up. In this meeting (D22-D38) Max displayed PowerPoint slides with bullets describing the nature of Project Hook, its content, and its expected effects on departments and platforms. He described the functional and stylistic changes proposed, listed the part numbers affected, and estimated per-part savings from switching to the new supplier. He also showed schematic diagrams of the new valve and listed its operational specifications, along with fluids with which it could operate compatibly. He further outlined (in bulleted format) mechanical durability requirements and the proposed materials, structures, assembly, operational, and safety testing. Since this meeting was not well attended, however, Max didn't receive much input on

issues he was concerned about. He turned to other communication devices to elicit the information he sought.

> For Max, email proved a more useful tool than meetings.
>
> Email can be relatively effective because you can track, you know, whether or not the person has actually opened it, and, if they have opened it, you can ask the question again. You can show up at their cubicle, knock on the door, and at that point you have them trapped. They can't get away from you. You sit down with them, take 20 minutes of their time. So in a lot of cases that was the way to do it. But, uh, that wasn't the obviously most *effective* way to do it because now you are individually chasing down people, which takes up more of the project manager's time. Also, if their opinion didn't agree with others' opinions, you're almost negotiating. You're going back and forth. Now this person has given me a different opinion on it than the last person. So you have to run this opinion by the last person to see if they agree, disagree, why (MZ.5.1).

Max said that the manager of the Value Engineering group, Chris, helped him identify people to talk to about the test plan. And Jon, still formally assigned to Styled Surfaces even though he worked mostly on an engine cooling system, helped him put together a matrix to show which structures and materials tests of which fuel tank configurations would reveal which information about the fuel valve's performance. Max finally completed the testing plan by the end of June 2000, and lab structures and materials testing of the new fuel valve began in July and continued through November 1. As testing proceeded, Max consulted Jon, whom he regarded as the technical expert for the project, about the forthcoming test results. Jon said, "He [Max] would usually stop over and say, 'I got the results. Can we spend 15 minutes looking at them?'" Then Jon and Max would email or arrange to meet or examine the results right then. Jon said, "Generally Max would always bounce it [his interpretations and conclusions] off me with a copy of the data [at hand]. Max would say, 'Do you see it the way I do?' Usually I did."

With Hook's quality targets signed off by the vice-president of engineering in February, a revised business case completed in April, and the test plan for the new fuel valve agreed to by all

platforms, and the Styled Surfaces, Fuel Systems, and Service groups in June, Hook exited Phase 1 in June 2000.

Unexpected issues

Having completed timely styling changes and with testing well underway, it seemed that the fuel valve from TG was on track for each platform's September or October Design Intent Build (DIB), a one-week on-the-assembly-line construction of vehicles embodying all the new-product projects scheduled to launch with the new model year the following July. According to the Company's product development method, the DIB produces components and assemblies "representative of the final design" (CPPDM.Def.3) and so marks the end of the design phase of development. The prototype vehicles produced during the DIB aren't salable, since they include some prototype parts (i.e., parts not formed with production-verified tooling); they are often used in extensive durability testing, which usually takes place at a road-test facility in another part of the country. When road-testing mechanics identify problems with the prototype vehicles, they document the problematic behavior, and any solutions they generate, in TIRs, or Test Incident Reports. TIRs are then sent to design engineers who work with the vehicle systems manifesting the problems.

In August KS reconsidered its earlier decision. In a letter that suggested its initial response was based on "internal miscommunication," KS requested an opportunity to bid on the fuel valve based on the new specifications. Its subsequently proposed redesigned valve, however, didn't approach the Company's cost targets, and the Company continued its discussions with TG.

In August 2000 Max submitted signed prints of the new fuel valve to EDS (Electronic Data Services), the group responsible for checking electronically recorded (by a modeler in each design engineering group) parts specifications and drawings, ensuring that the engineering prints are signed by the appropriate people across the organization, and officially "authorizing" parts, thus transferring it to VADAR, the Company's electronic repository of authorized engineering drawings. Authorization also electronically updates each platform's Bill of Materials. Submitting parts for authorization is a significant turning point in a new product project because, once parts are "authorized," changing them requires generating formal Engineering Change Notices, including new drawings, and circulating them to people in the product development center and the plants in order to obtain their signatures.

At the end of August Max held the Phase 2 technical design review, to which 21 people were invited, 11 accepted, and 7 showed (D5). In the review (D6-D17) Max used PowerPoint slides with bullets to summarize the few Test Incident Reports (TIRs) opened and closed for the project to date and the status of prints and their authorization. (These TIRs documented problems existing before the new fuel valve project; Max transferred these TIRs to the COEs, that, after some investigation, he believed were responsible for the parts or for creating the symptoms documented.) He reviewed the testing conducted to date by the lab and by the new prospective supplier, TG, using slides with summary bullets as well as charts showing fuel flow and strain level comparisons with the existing valve. He also showed slides listing the different types of testing still scheduled for the new valve. At this meeting, a member of the Service group raised again the issue of "siphoning," a situation in which the fuel valve could drain the fuel tank completely while in the "on" position, even though it should leave a few gallons in the tank unless switched to the "reserve" position. This Service group member had actually

experienced a siphoning problem on his (older model) vehicle. Max agreed to investigate (D18) the likelihood of siphoning and reconfirmed that TG believed the proposed vent near the top of the fuel filter would eliminate the siphoning possibility.

The mock-up fuel valve for each platform was completed by August 31 and placed in the mock-up area of the product development center, accessible to all employees.

Parts and the bill of materials for the fuel valve were authorized by EDS on September 5, 2000 (D58). Max updated the PAR/Business Case for Hook on September 11, 2000.

During the week of September 11 platforms D and X completed their DIBs; during the week of October 9, Platform S had its DIB; and Platform F completed its DIB the week of October 30. Each DIB used prototyped fuel valves provided by TG.

Sometime in the fall of 2000, perhaps late October or early November (Max could not positively recall the time-frame), a fuel valve whose nipple was separated from the valve body appeared on Max's desk (MZ.6.2-4).

> I believe it was [from] a DIB bike. The reason I say I believe that is that I received no documentation with it. There was a broken part on my desk. Somebody dropped off the part.... I think what happened is that the fuel valve was done with testing... and one of the mechanics was removing the fuel valve, and he took the pair of pliers or something similar and was yanking on either the fuel line itself or the fuel line nipple and was apparently able to work the nipple out. So he separated the nipple from the fuel valve, which is obviously not acceptable because if the person, if the end customer—I guess I'm not sure why the end customer would do that, unless they had to change the carburetor or something, but anyway. The press fit between the brass nipple on the fuel valve and the body itself was not tight enough then to prevent that from happening. But then after that, I took out several other parts and, you know, essentially pulled them apart to see how much [pressure] it took to actually separate the two. And it was a little bit on the low end. I believe it was like, well, anywhere from 90 to 120 pounds, 130 pounds, to separate the parts. So we increased that then to 280, 290, something like that.

To remedy this, Max initiated design changes to the diameter of the nipple to increase the press fit between it and the valve body.

In this same timeframe (October – November 2000), Brad in Developmental Purchasing sent the PPAP checklist to the prospective supplier TG. PPAP is the Company's certification that each supplier has run at least 300 parts meeting specifications using production tooling and provided validation of its inspection and qualification processes (JG.1.3). TG agreed to a target submission date of December 15, 2000, for its compliance with the Company's PPAP. Also in this timeframe Charles, who recently transferred into the Fuel Systems COE, told Max that the engineering print's call-out for the new fuel valve showed the incorrect mesh size for the fuel filter. The print specified the mesh as 250 microns, but the filter in use was 300 microns. Max agreed to make the specifications for the new valve 300, to match the current filter, but didn't view the change as urgent, since no problems were being reported with the tested and prototype valves using the 250 mesh.

On November 1 lab testing of the new fuel valve was completed. Two days later the DFMEA and PFMEA were updated with Derek, the manufacturing engineer resident at the Product Development Center, and Chad, who took had taken Jon's place in Styled Surfaces when Jon moved on to powertrain projects. Max also invited platform representatives to participate, but he said, "I remember turnout for those being pretty anemic." Project Hook officially exited Phase 2 on November 20.

Early durability testing conducted at road-testing facilities using DIB vehicles containing prototypes of TG's new fuel valve confirmed that siphoning remained a problem, despite the filter vent proposed to solve the problem. Modeling, experimentation, and bench testing by Max

led him to change the component's design by increasing the press fit between the filter and the valve to eliminate the possibility of siphoning.

In late November, Brad in Development Purchasing moved to another position, and Jack took over Developmental Purchasing responsibility for Project Hook. In mid-December, TG submitted its parts for its PPAP certification. According to Jack, TG's first submission was incomplete.

About this time Max submitted to EDS engineering change notices for the fuel valve, reflecting changes to parts in order to address the issues related to siphoning and the separability of the valve body and nipple. These were processed within a few weeks. Additionally, Max communicated these changes to prospective supplier TG and told Jack in Developmental Purchasing that revised parts would be available for the late February or early March FPE, an on-the-assembly-line prototype build of vehicles embodying all new product efforts but, unlike the DIB, this time using production tooling.

In early January 2001, 9 or 10 TIRs were generated and sent to the Fuel Systems COE because mechanics road-testing the DIB vehicles found "junk in the carburetor" after relatively few miles had been accumulated. The person in Fuel Systems receiving the TIRs was not knowledgeable of the fuel valve changes; though he recognized that the documented problems didn't arise from recent fuel system changes, he made no effort to find out what project or group might have made changes that caused these symptoms and then transfer the TIRs to that group. Since Max didn't receive the TIRs, at the time there was no connection made between the 250 micron mesh size of the new valve's filter and the carburetor problems. Jon, the engineer who knew most about the fuel filter (besides Max), who might have made the connection, was working on powertrain development projects. In January Max did receive a few TIRs from the

main road-test facility related to the fuel valve, one saying that the shut-off valve was "hard to turn" and the other reporting "stumble" when the vehicle was low on fuel. Each of these TIRs was difficult to resolve. Max requested that the parts be sent to him for investigation, particularly chemical analysis of the seals. But there was a considerable delay in his receiving the parts, partly due to administrative inefficiency, and partly from reluctance to dismantle vehicles urgently needed for additional road-testing so that validation schedules for other new product projects were to be maintained.

Late in January TG submitted parts for its second effort to obtain PPAP certification and passed the Company's requirements for production tooling on January 29, 2001 (D59). With TG certified as a supplier, Jack's main remaining Developmental Purchasing duty was to provide the parts transmittal sheets to the plants. The parts transmittal sheets document (JG.1.2) that the part drawings are authorized, the pricing is agreed on, the packaging for the parts is suitable to the Company's needs, and the packaging quantities meet the assembly plant's needs. After Developmental Purchasing delivers a parts transmittal sheet to Operations Purchasing, then responsibility for purchasing these parts is effectively transferred to Operations Purchasing, which can simply cut a blanket purchase order based on the MRP (manufacturing requirements plan) based on the information provided. Jack sent parts transmittal sheets to plants Y (making vehicles for platforms F, S, and D) and K (making Platform X vehicles) shortly after TG passed the PPAP certification.

In early February 2001 Operations Purchasing at Plant Y called Jack in Developmental Purchasing to ask if the DIB fuel valves should be used in the FPE (first production event) or scrapped. Jack confirmed that the DIB prototype fuel valves should be purged because there had been changes to the valve after the DIB; Plant Y should order new fuel valves from TG. Jack

also looked at the on-line purchasing system and confirmed for himself that the Plant K had placed an order for new fuel valves from TG for the FPE.

In February, Max conducted chemical analyses of the problematic fuel valves received from the road-testing facility. "Some looked absolutely fine," he said. "Others you could tell there was some stuff getting past the [filter] mesh and gumming up the parts." A clear-cut solution wasn't obvious, though. While the TIRs documented problems with fuel valves on platform S and D vehicles tested in the main road-test facility, the Platform F vehicles using the same fuel valve manifested no problem (though these were few in number, since many F models have electronically fuel-injected engines), and Platform X vehicles tested in another road-test facility displayed no problems. Personnel at the main road-test facility suspected something was contaminating its fuel; they flushed the facility's holding tank and replaced the tank's filter. In mid-February, TIRs about fuel valve problems stopped.

During the week of February 26 Platform F successfully carried out its FPE at Plant Y. During the week of March 5 the Platform D carried out its FPE at Plant Y. That same week at Plant K, however, the Platform X FPE experienced problems centered on the new fuel valve. Max, at K for the build, spotted the problem, recognizing that the nipple on the fuel valve "looked different," that is, not like the updated part. When Jack received a call on his pager that week from the Platform X Operations Purchasing lead at the plant notifying him of the problems, he called TG to confirm which version of the fuel valve it had shipped to Plant K (JG.1.6). TG said that Plant K had canceled the order. After talking with Plant K Operations Purchasing people about the canceled order, he learned that a purchasing person had looked in the new parts crib before the FPE and had seen numerous fuel valves left from the DIB and then canceled the order of new parts, not knowing that the fuel valve had undergone design changes after DIB. To

prevent additional problems during FPE builds, Jack took digital pictures of the old and new fuel valves and sent them to all the platform purchasing leads to make sure that the DIB parts were purged. To remedy the XL FPE vehicles that had obsolete fuel valves, Jack asked TG to shipped Plant K's canceled order of valves to the Product Development Center, and Max kept track of where each FPE vehicle went and retrofitted each of them with a new, correct fuel valve. Platform S's FPE was completed uneventfully at Plant Y a week or so later.

In early March Max received the January TIRs describing "junk in the carburetor," when the Fuel Systems group finally transferred them to him. He then concluded that the wrong mesh size (250 micron mesh, rather than 300) had generated, or at least contributed to, problems that manifested in the carburetor.

> [W]hen I got them [the TIRs] I was totally irritated by the fact that some of them, you know, were more than 100 days old when I got them. So even at that point--now luckily we knew what was going on with them, but if I had to investigate something like that, I've got nothing—"junk." It's a hundred days old. You had a hundred days' worth of fuel running through that. You've got a hundred days' worth of lost information. So in this case it wasn't really particularly relevant because we knew that we had the wrong filter mesh (MZ.11.2).

He also reinterpreted the TIRs concerning "stumble" and the switch being "hard to turn" as resulting from insufficient filtering allowing "junk" to clog the valve's mechanisms.

About March 15, Max submitted six engineering change notices to EDS. These included addressed the 300 micron filter specification but also documented additional specifications regarding fluid compatibility and minor dimensional revisions to make the Company's measurements (in English units) consistent with the supplier's measurements (in metric units), in order to prevent tolerance or inspection problems. About 10 days later EDS rejected four of the six engineering change notices because, the department said, the notices included "no drawings." Max was unable to learn from EDS what has happened to the remaining two change notices he

had submitted. After discussing the matter with Bob, a manager of a nearby group (as Value Engineering currently had no manager; Chris had moved to a different job) who had reviewed the change notices and drawings before Max had submitted them, Max resubmitted the four change notices with a note from Bob verifying that the drawings had been submitted to EDS with the original change notices and therefore must be in possession of EDS. The note also requested the status of the other two change notices.

On March 27, 2001, Project Hook exited Phase 3 on the condition that it retrofit Platform D FPE vehicles with 300 micron mesh filter so that they could be used for additional vehicle validation road-testing (D59).

A couple of weeks later the missing two engineering change notices were found at Plant K and the remaining four changes were processed by EDS, so all the change notices were officially authorized by late April or early May.

At the pre-production build on the assembly line in late May, there was one small problem, Max said. The line supervisor of the Platform X at Plant K called Max and said that "the tops of the fuel filter were popping off." Apparently the weld process for fuel tanks at Plant K was leaving tailings or dross inside the rim, and assemblers were essentially deforming the fuel filter to get it into the tank. Max asked TG to make the nipples slightly longer to ease assembly, but the problem was more fundamentally addressed by having welders clean with a rubber rod the hole where the fuel filter would be placed and ensuring that assemblers knew not to squeeze the filter during assembly.

No post-launch problems have been reported, and TG is viewed as performing well as a supplier. Final per-part savings on the fuel pump ranges (depending on the platform) from $7.23

to 7.77, and the final aggregated annual savings is estimated to be more $1 million again, due to increased production volumes of vehicles with carbureted engines.

Appendix C to Chapter 4: Table of interdepartmental interactions during Project Hook

Date	Purpose	Actions	Artifacts	Who—Dept.	Problem Identified	Problem Resolution
02/00	Styling mock-up review	Looking at prototype	Prototype produced by prospective supplier TG	Max—VE Larry—ST	Base should be blacker (P)	Supplier paint the part
02/00—07/00 (several meetings, some one-on-one)	Prepare testing plan	Talking about what tests would prove the valve safe for 16 fuel tank configura-tions	Matrix showing tanks, possible tests, and which tests would work for which tanks; Prototype of component	Max—VE Jon—SS George—SS Lance—PF Ric D.-PF Rob—PS Joe K-SL Tom D-AM Jeff A-PX	Not clear who to talk to (O) No black and white answers (O, P)	Keep asking until Max satisfied no one knows more than he does about reasonable plan to proceed
03/00	Technical design review, Phase 1	Showing slides; Talking; Passing around component prototype	PowerPoint slides, including words and schematic drawings; Summary sheet; Prototype of component	Bill H—PF Jon—SS Chris—VE	none	

Date	Purpose	Actions	Artifacts	Who—Dept.	Problem Identified	Problem Resolution
06/00	Test plan review	Talking	Overheads of spreadsheet showing measurable parameters of each type of test	Max—VE Jon—SS Chris—VE Joe K—SL/T Lance—PF George—SS Deepak—QR	?? (P)	Confirmed test plan reasonable
4/00	Prepare DFMEA, PFMEA	Prototypes	DFMEA/ PFMEA	Max—VE John S—MEY Derek—MR Amy C—Y? George S—SS Jon—SS Possibly others	??	??
08/00	Technical design review, Phase 2	Showing slides; Talking; Passing around prototype (pointed to some parts during presentation)	PowerPoint slides, including words and graphs of test results; Prototype of component	Max R—SV Rob—PS Joe K—SL/T Brad—DP Rod—Y? John—Y? Bob L—PD	Question on pressure resistance (P) Siphoning (P)	Confirmed pressure resistance specifica-tion Confirmed TG change should prevent siphoning
10/00	DFMEA/ PFMEA Update	Prototypes	DFMEA/ PFMEA from previous meeting	Max—VE Jon-SS George—SS Derek—MR John S—MEY		

Date	Purpose	Actions	Artifacts	Who—Dept.	Problem Identified	Problem Resolution
10/00	Altering DIB vehicle for road testing	Finding note on Max's desk Max conducting own separability tests	Fuel valve with nipple pulled out Prototype valves	Mechanic in absentia—T Max—VE	Press fit between valve body and nipple insufficient to prevent manual separation (P)	Change diameter of nipple
10/00	Chatting in passing	Talking	None	Chad—FS	Spec for filter says wrong micron size (P)	Change spec to match micron size filter in use
10/00	DIB Have Manufact uring review parts	Taking parts to Plant K, assembly line	Prototyped component	Derek—MR ??—AY ??—AK ??—MEY ??—MEK	English-unit wrench on assembly line doesn't fit metric nut on new part (P)	Acquire metric-unit tool for assembly line?
11/00	Update DFMEA, PFMEA	Talking	Graphs of test results	Max—VE Derek—MR Chad—SS	-- (P)	

Date	Purpose	Actions	Artifacts	Who—Dept.	Problem Identified	Problem Resolution
11/00	Project lead getting results from RTF	Reading TIRs Max conducting own hardware tests	Electronic and printed TIRs Prototyped parts	Max—VE ??—RTF	Siphoning still occurs (P)	Increase press fit between filter and valve
01/01	Project lead getting results from RTF	Receiving TIRs from RTF	Electronic TIRs	Max—VE ??—RTF	"Stumble," "switch hard to turn" (P)	Max awaits used parts for analysis
02/01	FPE	Watching build at Plant K	Prototype vehicle	Max—VE ??—OP ??—A ??—MEY ??—MEK	Plant K used (obsolete) DIB part for FPE (O)	TG expedite updated parts; Keep track of FPE vehicles for retrofitting updated part
02/01	--	Receiving parts from RTF	Prototype parts used in road-testing	Max—VE	"Lots of junk" clogging fuel valve (P)	RTF flushes fuel holding tank

Date	Purpose	Actions	Artifacts	Who—Dept.	Problem Identified	Problem Resolution
03/01	--	Receiving TIRs from Fuel Systems group	Printed TIRs	Max—VE	Junk in the carburetor (P)	Specify filter mesh as 300 micron; reinterpret previous TIRs as resulting from wrong filter mesh size and from particulates in the RTF fuel storage tanks

Departmental Abbreviations:

AK	Assembly from Plant K
AY	Assembly from Plant Y
AM	Applied Mechanics
DP	Developmental Purchasing
FS	Fuel Systems
MEK	Manufacturing Engineer from Plant K
MEY	Manufacturing Engineer from Plant Y
MR	Manufacturing in Residence at PDC
PD	Platform D
PF	Platform F
PS	Platform S
PX	Platform X
OP	Operations Purchasing
QR	Quality and Reliability
SL	Structures Lab
SS	Styled Surfaces
ST	Styling
SV	Service
T	Testing (place unknown)
RTF	Road-Test Facility
VE	Value Engineering
Y?	Representative from Plant Y, unknown title or department

Other Abbreviations:

DFMEA	Design Failure Mode Engineering Analysis
DIB	Design Intent Build (plant assembly of functioning vehicle using prototyped parts)
FPE	First Production Event (plant assembly of functioning vehicle using production-tooled parts)
(O)	Organizational or administrative problem
(P)	Product problem
PFMEA	Process Failure Mode Engineering Analysis
TG	Supplier of fuel valve component
TIR	Road-Test Incident Report (from RTF)

Inferences from examining the table of interdepartmental interactions

Identification of several significant problems took place physically outside of design engineering work area, when people not in design engineering were present. Several problems were identified by visual inspection of prototype hardware. I infer that cross-boundary interaction identifies problems in the project-in-process.

With the exception of the original DFMEA and PFMEA preparation and update review and the 08/00 technical design review, manufacturing did not participate in the cross-departmental meetings unless they were prototype builds at the plant. Assembly participated only in prototype builds at the plant. (That may be to be expected, since the fuel pump was not a high-visibility, high-change project. It is unlikely that Max would have invited manufacturing engineers to make a special trip to take part in his project meetings. If manufacturing engineers were already on-site at the PDC, and Max was aware of that, then perhaps they would have been invited to participate.)

Geometric integration testing took place with Pro E modeling and when Max placed prototype fuel pumps on the mockup vehicles at the PDC, but operational integration testing did not take place until road-testing was conducted at RTF with vehicles constructed at the DIB.

Problems that are administrative in nature (such as Plant K's practice of not purging prototype parts after DIB) can appear later as product problems (junk in the carburetor because the wrong filter mesh size and perhaps the wrong nipple was on prototype parts). Product problems (such as incorrect mesh specification on the engineering drawings) can appear as administrative (a parts-prints mismatch that apparently has no bearing on functionality). Furthermore, problems manifesting in the product can originate in non-product practices or procedures that affect product development efforts but are not documented. (The particulates in the carburetor may have come from the fuel storage tanks at RTF, but the maintenance and flushing of the storage tanks is not documented. The project manager learned of this possible cause of the TIR-documented problems socially, not procedurally or through analysis of the product under development.)

Problems manifesting in one part of the vehicle can originate in other parts of the vehicle. There is no obvious mechanism to link problems' symptoms and sources if expertise about systems where the problem is originating and systems where the problem is appearing is physically and socially (through reporting structures) distributed.

There is no obvious way to ensure how project team members can know who people of expertise are and how and when people of expertise talk to each other. Much critical information exchange is occasioned by chance and by social channels.

Appendix D to Chapter 4: Model documentation

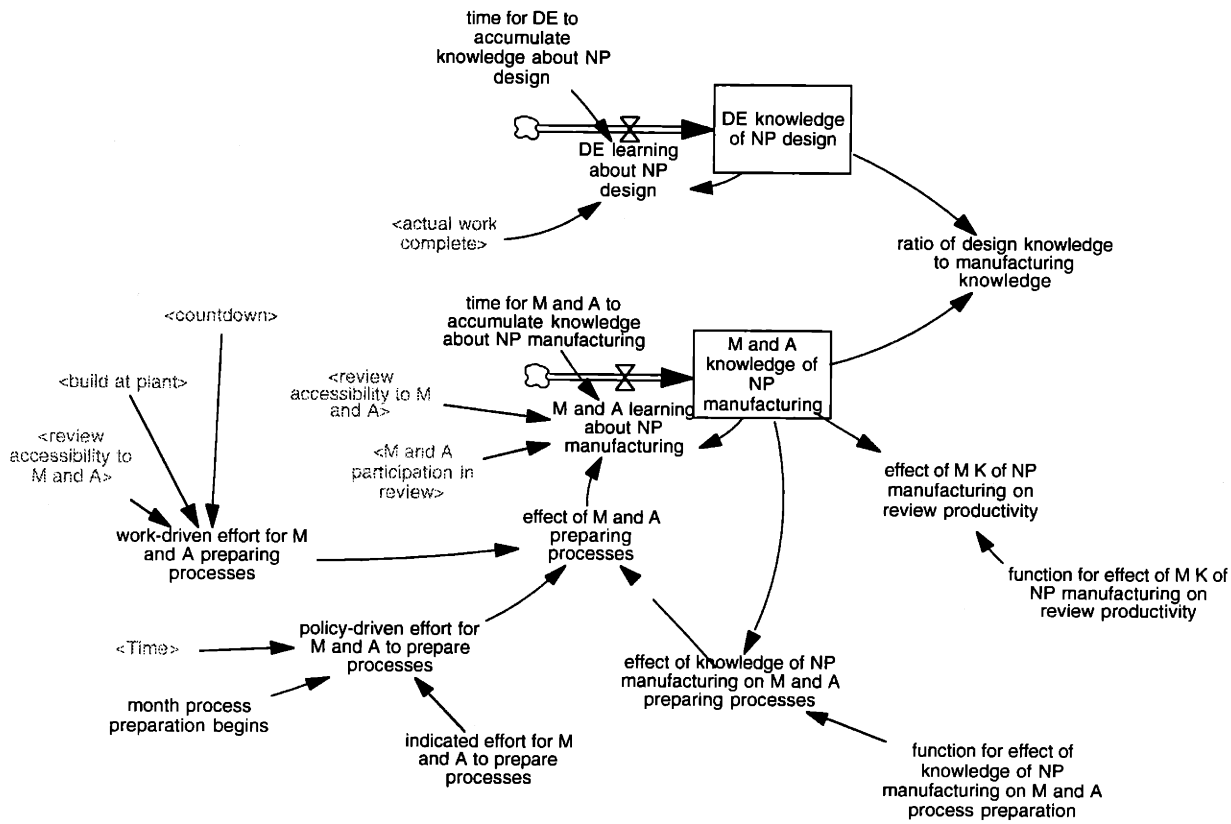
The model was constructed in Vensim®, and the simulations described in Chapter 4 were produced using the following command file.

```
SIMULATE>SETVAL|review A=5
SIMULATE>SETVAL|review B=9
SIMULATE>SETVAL|review C=100
SIMULATE>SETVAL|review D=100
SIMULATE>SETVAL|initial error fraction=.6
SIMULATE>SETVAL|month of 1st build at plant=13
SIMULATE>SETVAL|month of 2nd build at plant=19
SIMULATE>SETVAL|M and A effort to participate in review=.5
SIMULATE>SETVAL|indicated effort for M and A to prepare processes=0
SIMULATE>SETVAL|DE effort to make artifact concrete=.5
SIMULATE>SETVAL|DE effort to make action like production=.5
SIMULATE>SETVAL|DE effort to make location like production=.5
SIMULATE>RUNNAME|current
MENU>RUN|o

SIMULATE>SETVAL|review A=4
SIMULATE>SETVAL|review B=7
SIMULATE>SETVAL|review C=10
SIMULATE>SETVAL|review D=100
SIMULATE>SETVAL|initial error fraction=.6
SIMULATE>SETVAL|month of 1st build at plant=13
SIMULATE>SETVAL|month of 2nd build at plant=19
SIMULATE>SETVAL|M and A effort to participate in review=1
SIMULATE>SETVAL|indicated effort for M and A to prepare processes=0
SIMULATE>SETVAL|DE effort to make artifact concrete=1
SIMULATE>SETVAL|DE effort to make action like production=1
SIMULATE>SETVAL|DE effort to make location like production=1
SIMULATE>RUNNAME|ideal
MENU>RUN|o
```

The model is presented in four views: Knowledge about New Product Development; Review Accessibility to Manufacturing and Assembly; New Product Development Work; and Metrics.

View 1: Knowledge about New Product Work



(01) DE knowledge of NP design=
INTEG (DE learning about NP design,0)
Units: dimensionless
The accumulation of knowledge about NP design held collectively by DEs at any point in time; a 0 to 1 indicator of the percent of everything there is to know about designing a NP model year correctly that DEs have already acquired by doing NP design work.

(02) DE learning about NP design=
MAX(0,(actual work complete-DE knowledge of NP design)/ time for DE to accumulate knowledge about NP design)
Units: 1/Month
The rate at which DEs collectively learn about a NP model year's designs, based on how much NP design work they have done correctly.

(03) effect of knowledge of NP manufacturing on M and A preparing processes=
function for effect of knowledge of NP manufacturing on M and A process preparation
(M and A knowledge of NP manufacturing)
Units: dimensionless

The nonlinear influence of how much M and A knows about a new product on M and A's ablity and inclination to prepare processes (planning, digramming, and experiementation) for producing the new products. Based on interview with ME who discussed artifacts that M and A can bring to reviews.

(04) effect of M and A preparing processes=
effect of knowledge of NP manufacturing on M and A preparing processes*
MAX("work-driven effort for M and A preparing processes",
"policy-driven effort for M and A to prepare processes")
Units: dimensionless

The learning that results from M and A devoting effort (based either on mounting pressure to launch NP efforts imminently or on a managerial policy to begin process preparation at a certain point in the development cycle); process preparation is more effective, the more that M and A already knows about producing the NP. Suggested in interview with ME.

(05) effect of M K of NP manufacturing on review productivity=
function for effect of M K of NP manufacturing on review productivity
(M and A knowledge of NP manufacturing)
Units: dimensionless

The ability of M and A to identify latent problems in NP efforts, as depending on the amount of knowledge plant personnel have about the forthcoming new product. Inferred from observed behavior of M and A staff in reviews and corroborated by ME in interview.

(06) function for effect of knowledge of NP manufacturing on M and A process preparation
([(0,0)-(1,1)],(0,0),(0.3,0.33),(0.5,0.54),(0.7,0.74),(0.8,0.84),(0.9,0.93),(0.95,0.97),(1,1))
Units: dimensionless

Nonlinear function to indicate that as M and A staff know more about a NP effort they will devote more effort to preparing processes for manufacturing and assembling it. Based on suggestion by ME in interview.

(07) function for effect of M K of NP manufacturing on review productivity
([(0,0)-(1,2)],(0,1),(0.3,1.5),(0.5,1.75),(0.65,1.85),(0.8,1.93),(1,2))
Units: dimensionless

Nonlinear function to indicate that as M and A staff know more about a NP effort, they are more productive when they participate in NP reviews with DEs and identify problems in the NP at a faster rate. Corroborated in interviews with DEs and MEs.

(08) indicated effort for M and A to prepare processes=
0
Units: dimensionless
A simulation lever with which to test the effects of various levels of effort by M and A staff to prepare fabrication and assembly processes for forthcoming NP.

(09) M and A knowledge of NP manufacturing=
INTEG (M and A learning about NP manufacturing,0)
Units: dimensionless
The accumulation of knowledge about NP manufacturing and assembly held collectively by M and A staff at any point in time; a 0 to 1 indicator of the percent of everything there is to know about producing a NP model year correctly that M and A staff have already acquired by participating in reviews they understand and investing in NP process preparation.

(10) M and A learning about NP manufacturing=
(MAX(0,MAX(review accessibility to M and A*M and A participation in review, effect of M and A preparing processes)-M and A knowledge of NP manufacturing)/ time for M and A to accumulate knowledge about NP manufacturing)
Units: 1/Month
Increase in knowledge about NP manufacturing and assembly issues acquired from participating in NP reviews with DEs (especially when the review is accessible to M and A staff) or from devoting effort to prepare production processes for the NP effort. Based on observations of reviews and interviews with MEs.

(11) month process preparation begins=
12
Units: Month
The month that M and A would begin thinking about processes to produce new products; in reality the timing depends on the scope of NP work (if, for example, the NP requires extensive new tooling, then process preparation would begin earlier), but for midsize projects M and A would seldom devote attention to NP earlier than a year before launch. Based on interviews with MEs and A staff.

(12) "policy-driven effort for M and A to prepare processes"=
IF THEN ELSE (Time>=month process preparation begins, 1,0)* indicated effort for M and A to prepare processes
Units: dimensionless
The effort that M and A devote to preparing processes for NP under development rather than current production. Based on interview with MEs.

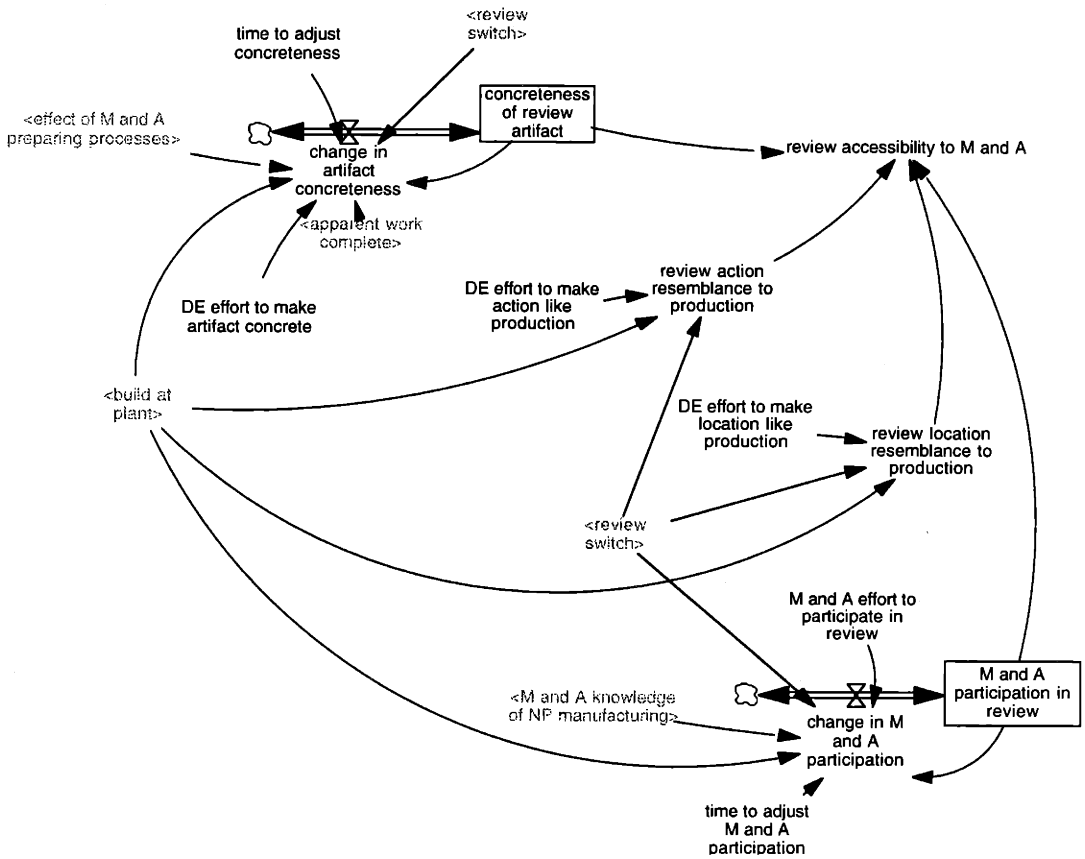
(13) ratio of design knowledge to manufacturing knowledge=
ZIDZ(DE knowledge of NP design,M and A knowledge of NP manufacturing)
Units: dimensionless
Dimensionless measure comparing the amount of DE knowledge of NP design to M and A knowledge of NP production processes. Used in simulation analysis to assess under what conditions reviews identify the most problems at the DE - M and A boundary.

(14) time for DE to accumulate knowledge about NP design=
1
Units: Month
"Soak time" for DEs to grow in understanding of NP designs completed correctly; primarily to indicate that it is not possible to learn from DE NP activities instantaneously.

(15) time for M and A to accumulate knowledge about NP manufacturing=
1
Units: Month
"Soak time" for M and A staff to grow in understanding of NP production issues; primarily to indicate that it is not possible to learn from M and A NP activities instantaneously.

(16) "work-driven effort for M and A preparing processes"=
IF THEN ELSE(build at plant=1 :OR:review accessibility to M and A>=0.9 :OR: countdown>=-4,1,0)
Units: Dimensionless
The effort that M and A devote to preparing processes for NP under development based on their engagement with the NP from imminent prototype builds to take place at the plant or other reviews highly accessible to plant personnel or an imminent launch date. Suggested by ME during interview.

View 2: Review Accessibility to Manufacturing and Assembly



(17) change in artifact concreteness=
IF THEN ELSE (build at plant=1,(1-concreteness of review artifact)/
time to adjust concreteness,(MAX(apparent work complete,
MAX(DE effort to make artifact concrete*review switch,
effect of M and A preparing processes))-concreteness of review artifact)/
time to adjust concreteness)
Units: 1/Month

Increase in tangibility of new product as it progress from idea to sketch to model to hardware, as a result of effort by DEs to obtain or create physical models or prototype parts, of effort by M and A to prepare production processes for a new product, or as a result of a prototype build (which requires functioning hardware) being scheduled. Inferred from observing progression of design work and from M and A's preference for working with hardware, expressed in ME interview.

(18) change in M and A participation=
IF THEN ELSE (build at plant=1,(1-M and A participation in review)/
time to adjust M and A participation, (MAX(M and A knowledge of NP manufacturing,
M and A effort to participate in review*review switch)-M and A participation in review)/
time to adjust M and A participation)
Units: 1/Month

The increase in review participation by M and A based on a review taking place at the plant (M and A's location) or on previous knowledge of the NP effort. Inferred from observation and corroborated in interview with ME.

(19) concreteness of review artifact=
INTEG (change in artifact concreteness,0)
Units: dimensionless

Dimensionless indicator of how much the object under development resembles the end product (0 is not at all, as bulleted list of anticipated features; 1 is complete end product resemblance, as in functioning hardware); concreteness of NP artifacts can accumulate through time as DEs complete NP tasks. Corroborated in interviews with DEs and MEs.

(20) DE effort to make action like production=
0.3
Units: dimensionless

The effort DEs devote to making actions undertaken with artifacts during interdepartmental reviews similar to actions M and A staff execute during fabrication and assembly (e.g., assembling prototype hardware) or actively engaging (e.g., walk-through of possible production processes); used as a simulation lever to test various scenarios for review timing and accessibility to M and A.

(21) DE effort to make artifact concrete=
0.3
Units: dimensionless

The effort DEs devote to making NP artifacts used during interdepartmental view resemble the end product that M and A staff with deal with (e.g., obtaining prototype hardware, or creating three-dimensional assembly drawings); used as simulation lever to test various scenarios for review timing and accessibility to M and A.

(22) DE effort to make location like production=
0.3
Units: dimensionless
The effort DEs devote to making NP review location like the environment in which M and A staff work (e.g., obtaining access to space for examination or assembly of prototype hardware); used as simulation lever to test various scenarios for review timing and accessibility to M and A.

(23) M and A effort to participate in review=
0.3
Units: dimensionless
Dimensionless indicator of effort that M and A will make to attend interdepartmental reviews when they do not yet know anything about the NP effort; value of 0.3 indicates that M and A staff make some but not extraordinary effort to attend reviews not held at the production plant. Corroborated in interview with ME.

(24) M and A participation in review=
INTEG (change in M and A participation,0)
Units: dimensionless
The accumulated willingness of M and A staff to participate in interdepartmental reviews, based on how much they have learned about (i.e., are invested in) the NP production issues. Corroborated in interview with ME.

(25) review accessibility to M and A=
concreteness of review artifact*review action resemblance to production* review location resemblance to production*M and A participation in review
Units: dimensionless
Dimensionless indicator for ability of M and A staff to learn about NP manufacturing and assembly issues from an interdepartmental review; based (equally, here) on the combination of the review's artifacts, actions, and locations resemblance to the customary work practices of M and A. Corroborated in interviews with DEs and MEs.

(26) review action resemblance to production=
IF THEN ELSE(build at plant=1,1,DE effort to make action like production)*
review switch
Units: dimensionless

Dimensionless indicator of the extent to which the actions undertaken with artifacts during a review resemble the actions M and A staff usually perform (1 is complete resemblance, as during DIB or FPE, prototype builds on the assembly line at a plant; 0 is complete lack of resemblance to M and A actions, as in listening to presentations; intermediate values based on the extent that DEs devote effort to devising review actions to resemble M and A work (e.g., creating process flow-charts for fabrication or assembly). Corroborated in interviews with DEs and MEs.

(27) review location resemblance to production=
IF THEN ELSE (build at plant=1,1,DE effort to make location like production)*
review switch
Units: dimensionless

Dimensionless indicator of the extent to which the place where a review takes place resembles the environment in which M and A staff usually work (1 is complete resemblance, as during DIB or FPE, prototype builds on the assembly line at a plant; 0 is complete lack of resemblance to manufacturing environment, as in DEs' offices at the PDC; intermediate values based on the extent that DEs devote effort to obtaining access to or creating location that resembles one of production and use, as in test lab or off-the-assembly line areas). Corroborated in interviews with DEs and MEs.

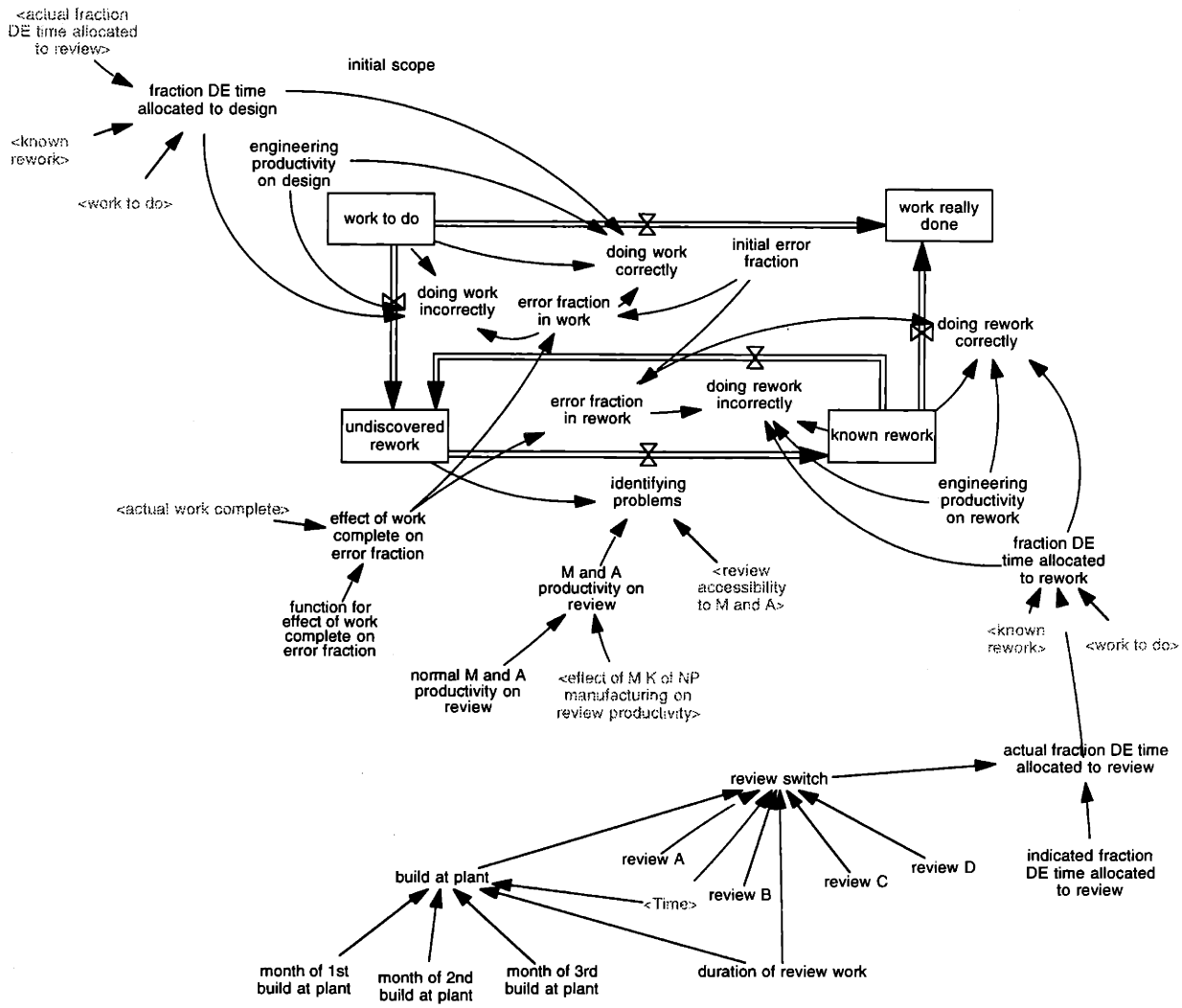
(28) time to adjust concreteness=
0.25
Units: Month

Time required for NP artifact to become more "concrete," based on DE progress on NP design work or rework or on DE effort to make tangible artifacts for interdepartmental reviews; primarily to suggest that NP designs do not instantaneously take on more "realistic" shapes as design work progresses.

(29) time to adjust M and A participation=
0.25
Units: Month

Time for M and A staff to accumulate more willingness to participate in interdepartmental reviews after learning more about the NP production issues through accessible reviews or by preparing production processes for the NP; primarily to suggest that M and A participation does not increase instantaneously with learning.

View 3: New Product Development Work



(30) actual fraction DE time allocated to review=
indicated fraction DE time allocated to review*review switch
Units: dimensionless

Percentage of DE time devoted to preparation for reviews with M and A by representing the current design in artifacts and arranging a location, time, and occasion for the review to take place; DEs spend time preparing for reviews only in the days (perhaps a couple of weeks) before they occur. Based on interviews of DEs indicating their efforts (and perceived cost to their other work) in staging reviews.

(31) build at plant=
IF THEN ELSE (Time>=month of 1st build at plant :AND:
Time<(month of 1st build at plant+duration of review work):OR:
Time>=month of 2nd build at plant :AND: Time<(month of 2nd build at plant+
duration of review work):OR:
Time>=month of 3rd build at plant :AND: Time<(month of 3rd build at plant+
duration of review work), 1,0)
Units: dimensionless

Switch to indicate a prototype build occurs at the M and A plant; DEs must spend effort on preparing, executing, and following up the build during the month that it occurs and cannot work on designs. Based on interviews with DEs in which they talked about preparatory activities for builds that interrupt other work and efforts to track and follow up on issues identified during prototype builds.

(32) doing rework correctly=
(1-error fraction in rework)*known rework*engineering productivity on rework
*fraction DE time allocated to rework
Units: tasks/Month

The rate at which DEs resolve problems in NP tasks without creating additional problems, based on the current probability of error in rework, their productivity on rework, and the fraction of available DE time devoted to rework.

(33) doing rework incorrectly=
error fraction in rework*known rework*engineering productivity on rework*
fraction DE time allocated to rework
Units: tasks/Month

The rate at which DEs work to resolve problems in NP tasks but create new problems (that will be identified in subsequent interdepartmental reviews); based on the current probability of error in rework, DEs productivity in rework and the fraction of available DE time devoted to rework.

(34) doing work correctly=
(1-error fraction in work)*work to do*engineering productivity on design*
fraction DE time allocated to design
Units: tasks/Month

The rate at which DEs initially perform NP tasks correctly, based on the current probability of oerror in initial work, DEs productivity in performing tasks for the first time, and the fraction of available DE time devoted to doing NP tasks.

(35) doing work incorrectly=
error fraction in work*work to do*engineering productivity on design*
fraction DE time allocated to design
Units: tasks/Month
The rate at which DEs initially perform NP tasks incorrectly, based on the current probability of error in initial work, DEs productivity in performing tasks for the first time, and the fraction of available DE time devoted to doing NP tasks.

(36) duration of review work=
1
Units: Month
The amount of time that DEs cannot work on designs each time a review occurs because they are preparing, executing, or following up on interdepartmental review work; one month is probably accurate for reviews highly accessible to M and A staff but probably longer than required for reviews not very accessible to M and A staff. Corroborated as simplistic but acceptable estimate in interviews with DEs.

(37) effect of work complete on error fraction=
function for effect of work complete on error fraction(actual work complete)
Units: dimensionless
The decreasing probability that tasks completed by DEs will require rework as they finish more tasks in a NP effort correctly. Corroborated in interview with DEs and PDO staff.

(38) engineering productivity on design=
0.7
Units: 1/Month
The (uncapacitated) rate at which DEs complete NP tasks for the first time.

(39) fraction DE time allocated to design=
MAX(0,(work to do/(work to do+known rework)-
actual fraction DE time allocated to review))
Units: dimensionless
The percentage of available DE time devoted to performing NP tasks for the first time, based on the how much design work is waiting to be done initially compared to how much design work is waiting for rework; in months when reviews are taking place no DE time is available for performing NP tasks for the first time; generously assumes that DE staff is always adequate for the work at hand.

(40) fraction DE time allocated to rework=
MAX(0, ((known rework/(known rework+work to do))-
actual fraction DE time allocated to review))
Units: dimensionless
The percentage of available DE time devoted to performing rework in NP tasks with identified problems, based on the how much design rework is waiting to be done compared to how much design work is waiting to be done for the first time; in months when reviews occur no DE time is available for performing NP tasks for the first time; generously assumes that DE staff is always adequate for the work at hand.

(41) engineering productivity on rework=
engineering productivity on design
Units: 1/Month
The (uncapacitated) rate at which DEs complete rework on NP tasks in which problems have been identified.

(42) error fraction in rework=
initial error fraction*effect of work complete on error fraction
Units: dimensionless
The probability that a NP task-with-an-identified-problem reworked by DEs will require rework again; decreasing as more NP tasks in a model year are completed correctly. Corroborated in interviews with DEs and PDO staff.

(43) error fraction in work=
initial error fraction*effect of work complete on error fraction
Units: dimensionless
The probability that a NP task performed by DEs for the first time will require rework later; initially high but decreasing as more NP tasks for a model year are completed correctly. Corroborated in interviews with DEs and PDO staff.

(44) function for effect of work complete on error fraction
([(0,0)-(1,1)],(0,1),(0.1,0.96),(0.24,0.88),(0.36,0.76),(0.5,0.55),(0.63,0.4),(0.75,0.3),
(0.9,0.27),(1,0.25))
Units: dimensionless
Nonlinear function to indicate that as more NP work is completed correctly, the fewer errors DEs will make in the work left to do. Corroborated in interviews with DEs and PDO staff.

(45) identifying problems=
undiscovered rework*M and A productivity on review*
review accessibility to M and A
Units: tasks/Month
The (uncapacitated) rate at which problems in NP tasks are identified during interdepartmental (DE and M and A) reviews, based on the amount of accumulated NP tasks with unidentified problems, the accessibility of the review to M and A, and M and A's productivity in the review (dependent on previously acquired knowledge of the NP effort). Corroborated in interviews with MEs and DEs.

(46) indicated fraction DE time allocated to review=
1
Units: dimensionless
The fraction of DE time devoted to preparing for, executing, and following up on reviews, during the months that they occur; assumes that in months when reviews occur DEs cannot get any design work done. Corroborated as simplistic but acceptable assumption in interviews with DEs.

(47) initial error fraction=
0.6
Units: dimensionless
The probability that a task done at the very start of work on new products will be done incorrectly; assumes that little about a NP is "firm" when work first begins, so the likelihood of rework is high.

(48) initial scope=
70
Units: tasks
Parameter indicating the number of NP tasks in a new model year requiring M and A participation in reviews with DEs to be validated or completed correctly. That such tasks exist corroborated in interviews with DEs and MEs (actual number varies with model-year scope).

(49) known rework=
INTEG (+identifying problems-doing rework correctly-
doing rework incorrectly,0)
Units: tasks
The accumulation of NP tasks containing problems that DEs and M and A staff know about, increased by identifying problems in NP tasks during interdepartmental reviews and decreased by DEs performing rework.

(50) M and A productivity on review=
effect of M K of NP manufacturing on review productivity*
normal M and A productivity on review
Units: 1/Month
The rate at which M and A can identify problems in a NP effort, based on how much plant personnel already understand about the NP effort (if they know more then they identify problems more rapidly). Corroborated with ME in interview.

(51) month of 1st build at plant=
100
Units: Month
Month (1 to 24) during development cycle at which the first prototype build takes place at the plant. Used as a simulation lever for testing the effects on actual work complete at launch of various timing of reviews and builds.

(52) month of 2nd build at plant=
100
Units: Month
Month (1 to 24) during the development cycle at which the second prototype build takes place at the plant. Used as a simulation lever for testing the effects on actual work complete at launch of various timing of reviews and builds.

(53) month of 3rd build at plant=
100
Units: Month
The month at which a hypothetical third prototype build could take place at the manufacturing and assembly plant. Used as a simulation lever for testing the effects on actual work complete at launch of various patterns and timing of reviews and builds.

(54) normal M and A productivity on review=
1
Units: 1/Month
The (uncapacitated) rate at which M and A could help identify problems in NP efforts if they have no knowledge of the new product effort.

(55) review A=
100
Units: Month
Month (1 to 24) during the development cycle at which the first interdepartmental review takes place. Used as a simulation lever for testing the effects of various patterns in review timing and accessibility to M and A.

(56) review B=
100
Units: Month
Month (1 to 24) during the development cycle at which the second interdepartmental review takes place. Used as a simulation lever for testing the effects of various patterns in review timing and accessibility to M and A.

(57) review C=
100
Units: Month
Month (1 to 24) during the development cycle at which the third interdepartmental review takes place. Used as a simulation lever for testing the effects of various patterns in review timing and accessibility to M and A.

(58) review D=
100
Units: Month
Month (1 to 24) during the development cycle at which the fourth interdepartmental review takes place. Used as a simulation lever for testing the effects of various patterns in review timing and accessibility to M and A.

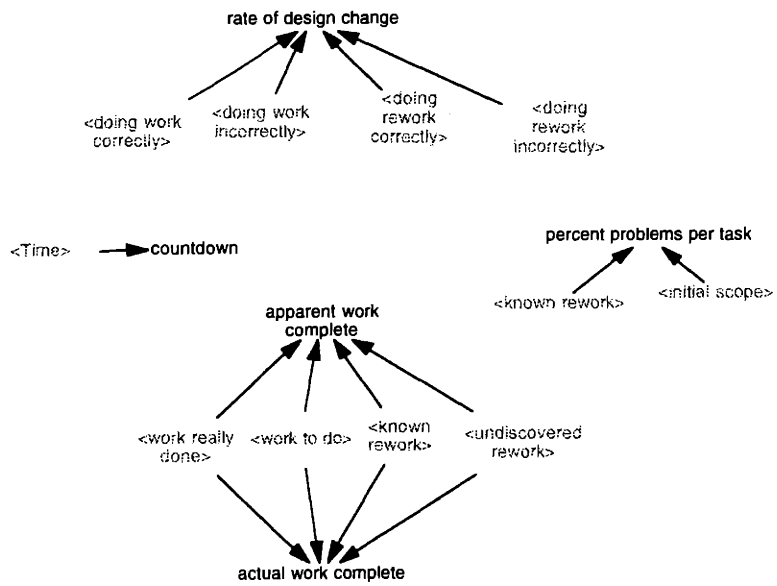
(59) review switch=
MIN(IF THEN ELSE (Time>=review A :AND:
Time<(review A+duration of review work):OR:
Time>=review B :AND: Time<(review B+duration of review work):OR:
Time>=review C :AND: Time<(review C+duration of review work):OR:
Time>=review D :AND: Time<(review D+duration of review work), 1,0)+build at plant, 1)
Units: dimensionless
Switch to make review-related variables active in the simulation at the times indicated by review and build simulation levers.

(60) undiscovered rework=
INTEG (doing rework incorrectly+doing work incorrectly-identifying problems,0)
Units: tasks
Accumulation of NP model-year tasks that have problems that have not yet been identified through interdepartmental reviews.

(61) work really done=
INTEG (doing rework correctly+doing work correctly,0)
Units: tasks
Accumulation of NP model-year tasks completed corrrectly.

(62) work to do=
INTEG (-doing work correctly-doing work incorrectly,initial scope)
Units: tasks
Accumulation of NP model-year tasks remaining to be performed for the first time.

View 4: Metrics



(63) actual work complete=
work really done/(work to do+work really done+known rework+ undiscovered rework)
Units: dimensionless
The percentage of NP tasks in a model year completed correctly at any point in time; since it accounts for rework not yet identified, the actual work complete is not knowable by DEs or M and A staff.

(64) apparent work complete=
(work really done+undiscovered rework)/(known rework+undiscovered rework+ work really done+work to do)
Units: dimensionless
The percentage of a model-year's tasks that employees believe that have completed correctly, based on the amount of work they have done correctly and the amount of work with problems they do not know about yet. Based on observations and experience that people forget to plan for rework.

(65) countdown=
Time-24
Units: Month
The number of months before launch, at any point in time.

(66) percent problems per task=
known rework/initial scope
Units: dimensionless
A dimensionless measure of the amount of unresolved problems in NP effort at any point in time. Analogous to Company's tracking "open concerns per new changed part" in internal company report C.

(67) rate of design change=
doing work correctly+doing work incorrectly+doing rework correctly+ doing rework incorrectly
Units: tasks/Month
The rate at which all designs for the NP model year are changing, based on all the DE activity on performing initial work or rework at a point in time.

Time bounds for model

(68) FINAL TIME =
24
Units: Month
The final time for the simulation.

(69) INITIAL TIME =
0
Units: Month
The initial time for the simulation.

(70) SAVEPER =
TIME STEP
Units: Month
The frequency with which simulation output is stored.

(71) TIME STEP =
0.125
Units: Month
The time step for the simulation.

Chapter 5

Toward a Theory of Two-Party Cross-Boundary Collaboration

Collaborating across boundaries becomes more important as work becomes more interdependent through increasingly complex products and processes and as organizations seek to interleave elements of their own operations with suppliers, vendors, financial markets, and customers. Interactions at the boundary bring to the fore the interdependence of roles, departmental expertise, or other aspects of the division of labor. Some cross-boundary exchanges are at least partially designed, as in the case of an organization's seeking to structure systematically interactions between design engineering and manufacturing and assembly during product development. Others emerge as new technologies, tools, or processes blur formerly accepted divisions of labor or bring into overlap occupations unaccustomed to working together, as when a new scanning technology makes obsolete the customary no-interaction doctor-technician division of labor. Whatever the instigator, the challenge for collaborating across boundaries arises from sources of distinction separating the parties: differences in language, tools, assumptions, objectives, or pace of work.

In this dissertation I have explored two cases of working across departmental and role boundaries. From these cases and literature on knowledge management, innovation, and structuration and practice theories, I proposed a theoretical framework for examining cross-boundary collaboration. The findings and explanations yielded by analyzing the cases in light of the emerging framework as animated by system dynamics simulation demonstrate the value of the framework's integration of several theories and the usefulness of simulation as a method to

explore (non)collaborative patterns through time. In Section 5.1 I recapitulate the framework and discuss conclusions from the cases about boundary-crossing work and the three observed failure modes leading to noncollaboration. Section 5.2 discusses practical and theoretical implications arising from this research, and Section 5.3 identifies current limitations and future directions of research on cross-boundary collaboration.

5.1 Recapitulating the theoretical framework

The theoretical framework builds on the lens articulated in Chapter 2, integrating three existing themes in organizational literature: in-the-moment activities, actors' accumulated resources, and recursive relationships between these that play out through time. It elaborates on each of these elements and incorporates research relevant to cross-boundary work in areas of knowledge creation, knowledge representation, and product development and innovation in ways consistent with dynamic theories of practice and structuration.

In the framework, participants of different practices hold distinct accumulations of knowledge. That knowledge is viewed as distributed among their minds and bodies but also embodied in the artifacts they use, the actions they undertake, and the spaces they occupy in daily work. Any cross-boundary activity therefore draws on elements of participants' practices. To the extent that people actively participate in a cross-boundary activity, they use artifacts, actions, and locations supporting their specialized expertise to communicate to others at the boundary. The timing of a cross-boundary activity in the flow of work is an additional dimension that affects the artifacts, actions, and locations available. To the extent that these dimensions are congruent with others' familiar ways of knowing and doing work, people

specializing in different disciplines can learn from the cross-boundary activity, thereby accumulating knowledge about the interdependent work and the roles they might play in it. When participants on both sides of the boundary learn from the joint activity, collaborative patterns unfold.

Three mismatches leading to uncollaborative patterns

Taken together, the framework and case study analyses point to several "mismatches" among elements that can lead to uncollaborative ways of working, patterns in which learning by one or both parties ceases. The first is a mismatch between dimensions of a cross-boundary activity and the participants it is intended to engage. Chapter 4's study of interdepartmental reviews during product development provides examples, when representatives from manufacturing and assembly were "too quiet," according to design engineers, during model-year reviews that primarily relied on presentations of engineering sketches projected onto a screen. Although plant personnel did not challenge design assumptions affecting their ability to manufacture and assemble the product at model-year reviews, at assembly-line prototype builds of the same designs, when they came to know the new product in the manner of work familiar to them, they identified many problems requiring design alterations. At prototype builds, manufacturing and assembly did not necessarily enter the review with more knowledge of the new product; rather, the accessibility of the plant-based, hardware-oriented interactions with design engineers allowed them to learn much more about it than in all the preceding months. Although Chapter 2 did not discuss it in these terms, one might also recast the experience of the technicians inexperienced in CT scanning at Urban hospital as experiencing a mismatch between their technical skills and the cross-boundary activity of working with doctors to manipulate the

new machine to produce scans, a mismatch that made it difficult for them to learn anything from the artifacts and language unrelated to their previously accumulated experiences of scanning.

An activity's accessibility becomes especially problematic when there is also an imbalance in amounts of role-specific expertise across the boundary. In both the cases studied, there were instances in which people with more knowledge took more control of the cross-boundary activity. In Urban hospital's first phase (in Chapter 2), doctors staffing the new unit arrived with some knowledge of CT technology, while technicians, skilled in other types of scanning, possessed no knowledge of the new type of scan production. Doctors perceived the technicians' inability to use the new machine as unwillingness to learn CT technology and began operating the machine themselves to produce scans. In Chapter 4's scenario, the Company's early reviews in product development were staged and executed by design engineers, the only ones who possessed much knowledge of the new product at that point. In both cases, people with less expertise for cross-boundary activities (though quite capable in other aspects of their practices) were effectively shut out from active participation at the boundary, even though they were present and attending to what was going on.

A third mismatch can occur when participants in a cross-boundary activity acquire knowledge that "belongs" to people across the boundary. Chapter 2's technicians at Suburban hospital provide an example of this. From early interactions with the CT-experienced doctor who was hired to deploy the unit, the technicians, who had accumulated some CT expertise at another facility, quickly learned not only how to produce scans proficiently but also acquired some rudimentary skill in recognizing pathology in scans. This was not threatening to the radiologist who first worked with the technicians, but when doctors with no CT experience were rotated into the unit, they were affronted by the technicians' understanding more than they about

how to read the scans. Technicians did not take control of the interactions with the doctors; they were deferential to them and "clandestinely" sought to instruct doctors about what to look for in scans. After several embarrassing role reversals, in which doctors asked technicians to interpret scans, doctors withdrew from the scanning area to minimize contact with technicians, not because technicians were exceedingly competent at producing scans but because they were demonstrating some competence in diagnosis, which the doctors considered solely their domain. (I did not recognize this kind of mismatch in my studies of product development interdepartmental reviews.)

Because cross-boundary activities unfold recursively as people use their skills in mundane activities at the boundary, and thereby gaining more expertise, feedback processes can serve to amplify or attenuate these mismatches. In Chapter 4's case, each early prototype build at the plant called by platform leader Matt provided manufacturing and assembly with highly accessible information about the product under development, thereby reducing the imbalance between the design and production departments' knowledge of new products. As development progressed, manufacturing and assembly's growing understanding of the new product kept them actively involved in identifying and resolving problems. Discovering and addressing problems through design alterations also increased design engineers' understanding of the new product; and as they advanced the new product work, they were more inclined to engage manufacturing and assembly in reviews that made use of hardware in addition to drawings. In Chapter 2's discussion of Urban hospital, initial imbalances in role-specific expertise grew more pronounced as doctors assumed more scanning responsibilities and thereby learned even more about how to operate the new CT machine. In both Surburban's first phase and Urban's final phase, on the other hand, the initial balance in expertise across the doctor-technician boundary was maintained

as both technicians and doctors grew in specialized skills through daily collaborative interactions.

Intervening in uncollaborative patterns

Since cross-boundary activities unfold within recursive feedback patterns, these knowledge mismatches are intertwined with one another, and an intervention to address one mismatch can favorably affect another kind. When, as described in Chapter 4, Matt staged prototype builds at the plant very early in development, he deliberately redesigned early design-manufacturing interactions to involve actively (and become much more accessible to) plant personnel. This allowed manufacturing and assembly to accumulate knowledge about the forthcoming new product at a rate that more nearly kept pace with design's understanding of the new product.

At Urban hospital, described in Chapter 2, the change in staffing for the CT units inadvertently shifted the three-month-long uncollaborative interaction between doctors and technicians onto a collaborative trajectory. When CT-inexperienced doctors began working with CT-inexperienced technicians, they interacted in ways that allowed each party to become competent in her role in working with the new technology. Thus the staffing rotation effectively re-balanced role-specific expertise across the boundary. Within the doctor-technician case described there was no intervention, planned or unplanned, that addressed realigning final-phase Suburban technicians' knowledge of CT diagnosis with their expected role. Yet as CT and other forms of computerized technology have become commonplace, standard operating procedures and technician-certification programs have legitimated technicians' knowledge of certain aspects of scan interpretation and pathology recognition.

Some cross-boundary activities are highly constrained and perhaps limit opportunities to redirect uncollaborative patterns to collaborative trajectories. In Chapter 2's case, several aspects of the cross-boundary interaction between doctors and technicians were fixed in that they were not manipulatable by participants. Interactions occurred in the scanning area, where technicians were expected to remain, although doctors could come and go at will. The artifacts of the interaction consisted of the new computerized tomography machine and the scans it generated. The primary action during this interchange was producing a scan useful to diagnosis, and, as was observed, sometimes technicians and sometimes doctors operated the machine to create scans. It is worth noting, also, that the timing of the interaction was not manipulated by either doctors or technicians; scanning took place when a patient appeared and lasted until someone, either technician or doctor, was satisfied that a useful scan had been produced. The dominant variable in the interaction became participation in the interaction, and this varied significantly, largely at the doctors' prerogative. Staffing the unit with more or less CT-experienced personnel and doctors' choices about whether and how to communicate with technicians during scanning appeared to form the primary levers for moving interactions from an uncollaborative pattern to a collaborative one, or vice-versa.

In contrast, in the design-manufacturing division of labor described in Chapter 4, many dimensions of most interactions were undefined, although the Concurrent Product and Process Delivery Method stipulated that interdepartmental interactions should occur. That is, aspects of the interaction were manipulatable in some way by someone. Except for the method-mandated prototype builds, timing for these interactions was discretionary. Who participated, the artifacts presented, the actions undertaken, and even the location for cross-departmental reviews were formally under the auspices of the project manager's decision-making. Thus project-managing

design engineers often defined the agenda for these interactions, although their choices about these aspects were certainly influenced by suggestions voiced by project team members, precedents established by other projects, and opportunities afforded by chance. As observed at the Company, and demonstrated by the model analysis, choices about these dimensions of interdepartmental interactions significantly affected who learned what. When design engineers structured interactions in ways that limited manufacturing and assembly's ability and inclination to learn about the new product under development, they not only slowed learning of the plant personnel but also delayed identification of latent problems, the solving of which could increase their own knowledge of the new product's design.

The research undertaken in this dissertation has underscored both opportunities and necessities for people to shape activities at the boundary to establish the possibility for collaborative interactions, in which all parties can learn more about interdependent work. In Figure 5.1 I represent this emphasis with additional arrows indicating that participants can design cross-boundary interactions to address the activity's inaccessibility to participants, imbalance in amounts of role-specific expertise across the boundary, and incongruence between the kinds of knowledge people accumulate from the interaction and their expected roles. Levers for intervention include choosing artifacts, actions, locations, and timing of activities in the flow of work, particularly to favor those with less expertise in the joint activities; considering who participates and their level of skill to manipulate the tools at the boundary; and redefining and aligning roles with desirable changes in types of expertise exercised at the boundary.

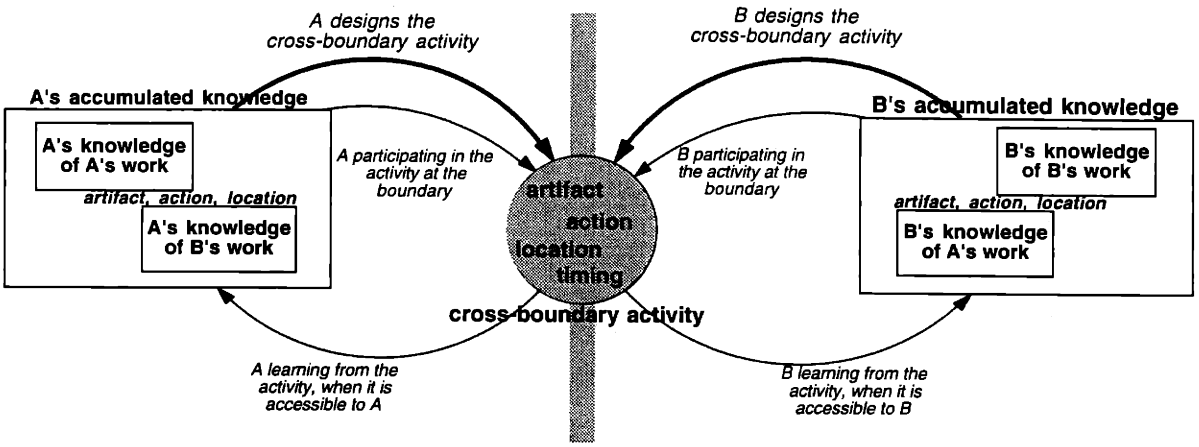


Figure 5.1: Designing cross-boundary activity for collaborative interaction

The contributions arising from the theoretical framework and the case study analyses using simulation center on providing better explanations of why noncollaborative patterns emerge and what interventions can redirect cross-boundary interactions to involve people actively and productively in interdependent work. Examination of relative expertise to engage in interactions at the boundary explains some of the differences in "structuring" observed in the field (Barley, 1986). But attention to the ways activities unfold, and particularly to the physical dimensions of micro-processes during cross-boundary activities, also offers insight into why some people learn and others do not; locations, artifacts, and actions affect who has a voice in an emerging practice at the boundary. Recognizing the enduring accumulations of resources and emergent activities and the recursive relationships between these provides a conceptual bridge with which resource-based views and enactment-oriented views of organizations may inform each other. Thus the framework helps discern the aspects of "context" on which to focus in a study of cross-boundary work. Simulating interactions between accumulations and activities helps check the internal consistency of the explanations suggested by the framework and allows

exploration of the effects of timing in interactions at the boundary on the desired organizational outcomes. Animating elements of the framework as applied to particular settings through system dynamics modeling provides a more comprehensive explanation of the dynamics of collaboration across boundaries.

Different knowledge, not just more knowledge

An adage asserts that a problem is never resolved with the same understanding with which it was created. The representation of knowledge in the models is limited in that it captures that *amounts* of knowledge may change as a result of cross-boundary activities, when in reality collaborative interactions can lead to new knowledge creation (Carlile, 2002). That is, they can generate new *kinds* of know-how, not simply increase the kinds of understanding originally brought to the boundary. Chapter 2's model made this explicit by representing that technicians could accumulate limited skill in interpreting CT scans; this possibility was inferred from Barley's (1986) detailed "scripts" revealing tensions between Suburban's doctors and technicians (in the final phase) as they discussed interpretation of scans. Although it is often hard to identify what new types of knowledge may emerge from cross-boundary activities, it is imperative that we consider the role of concrete artifacts, actions, and locations of cross-boundary activities in its generation.

If knowledge is competence to act (Bourdieu, 1980/1990; Carlile, 1997), then the range of actions, artifacts, and locations possible during a cross-boundary interaction affects what is knowable, by whom. These aspects of an interaction directly limit or enhance a participant's ability and inclination, relative to her existing skill-set, to apprehend the work at stake. Since boundary-crossing activities can change our cognitions, what we choose to represent in these

interactions—and those representations' proximity to a participant's customary practices—determine what kind of knowledge emerges in the course of cross-boundary problem-solving, as well as who accumulates it. The person or people to whom hierarchical authority or procedural or chronological precedence has given the widest range of choice in aspects of who participates and of the artifacts, activities, location, and timing of the interaction are the more powerful people in the cross-boundary activity. Their definitions of these aspects influence the emerging articulation of "the problem" (Suchman, 1995) and thus its resolution or dissolution.

5.2 Implications for practice and theory

This research suggests several implications for theory and practice. They include considering ways that the physical flow of work is intertwined with enactment of social patterns, viewing relative expertise as a concept of timing to complement calendar-driven and sequential process-flow perspectives, and using modeling and simulation to deepen theorizing about organizational dynamics. Below I discuss these ideas and offer some additional thoughts about practical ramifications of intervening to establish and maintain collaborative patterns, including an explanation of why addressing one boundary, ironically, can create another.

Physical flows of work and emerging social patterns intertwined

Qualitative and simulation analyses of the case studies suggest that the flow of work and social patterns are intertwined in feedback structures that influence the outcome of both. By physical flow of work, I mean the within-practice tools, places, and concrete manifestations of work-in-process, along with the pacing inherent in these, as well as intangible pressure

accumulating from work not yet done. By social behaviors I mean customary ways of interacting within and across categories of role, discipline, and department. Operations management studies have typically focused on understanding the flow of work by exploring the capacity of physical and technological systems. Organizational research has more commonly focused on social behaviors abstracted from their physical contexts. By representing explicitly both the flow of work and social behaviors as they relate to cross-boundary activities, I have explored, more thoroughly than possible by emphasizing one at the expense of the other, how to shape and intervene in cross-boundary interactions to make desired outcomes more likely.

Practically, the focus of cross-boundary interactions is often on the physical flow of work rather than on unfolding social dynamics. Working across boundaries is often propelled by demands in the content of work instead of desire to learn more about one's own or another's work through sustained interaction—learning serves the work at hand, rather than the other way around. It is useful, however, to consider how social dynamics can influence the physical flow of work in practice. For example, staging "costly" reviews to identify problems early in the development cycle can be socially and professionally unrewarding for design engineers. It may not be surprising then, without a change in organizational culture that leads people to value problems rather than regard them as interruptions to "real work," there is little investment in early cross-boundary interactions to surface problematic issues with the new product's design and manufacture.

Theoretically, it is useful to consider the physical flow of work as it influences patterns of organizing. If physical characteristics of the new CT technology, for example, had not brought doctors and technicians into the scanning area together, it is likely that the division of labor customary to X-ray and other types of scanning (technicians produce scans and leave them for

doctors to pick up and interpret later) might have prevailed from the beginning. With computerized tomography, however, it was no longer possible for a technician to produce a scan useful to diagnosis without some knowledge of how to recognize pathology in the image; the separability of scanning and diagnostic tasks became blurred. With ultrasound and more advanced computerized scanning, the separability of scanning and diagnosing has become even more obscured. Recognition of changes in the nature of technicians' work can provide leverage for understanding why certain doctor-technician patterns of interaction emerge.

My point is not to advocate a particular way of representing the flow of work and its effects on and influences by social behaviors in the setting studied. Rather, in the spirit of "bringing work back in" to organizational research (Barley and Kunda, 2001), I suggest that including relationships between the flow of work and social patterns can improve our explanations of dynamics in each.

Another view of timing in cross-boundary work

While the idea of time is inherent in any conceptual model of dynamics, the effects of timing of particular events within the flow of recursive patterns through time also merit exploration. Each of the setting-specific models posed here provides an internally consistent explanation for more than one pattern of behavior observed in those settings. That a single constellation of accumulations and activities can, with different initial conditions and under different policies, generate more than one pattern of behavior through time makes evident that differences in patterns are not completely explained by attributing cause to different "timing" of events in the situations. One must at least ask, "Timing of *what?*" In the cases discussed, I find that relative expertise to engage in activities at the boundary provides a view of timing

complementary to that provided by calendars and sequential process flows. By emphasizing relative expertise as an indicator of power to act in a cross-boundary interchange, this notion of timing differs from other research on timing (e.g., Zerubavel, 1981; Albert, 1995; Ancona and Chong, 1996). In this light, timing may be viewed as a shorthand way to ascribe a particular, ephemeral layout of relative position—i.e., the "structure," or objective relations (Bourdieu, 1980/1990)—of the cross-boundary field of play. In the case on new scanning technology, for example, relative expertise across the doctor-technician boundary provides an explanation of the different hospitals' patterns of behavior that renders timing of staff rotations incidental. What matters is not that CT-inexperienced entered the unit on day 21 or on day 106 but that, when they did, they found that technicians knew more or less than they about how to interpret scans.

In the case on product development, relative expertise across the design-manufacturing boundary explains *why* timing of reviews is important. Early reviews accessible to manufacturing and assembly help re-balance new product knowledge across the design-manufacturing boundary. In this way relative expertise at the boundary offers a corresponding view of timing in collaborative work that fills out the picture created by calendar dates and process sequences. The simulated explorations of the effects of interdepartmental review timing and accessibility on the desired pattern of work suggest reviews take place in ways and at frequencies to keep manufacturing and assembly staff knowledge of new products apace with design engineering's understanding. In fact, advocacy in product development literature to hold interdepartmental reviews early in the development cycle may be construed as advice to increase knowledge of the new product among non-design-engineer staff early in the development cycle. An implication is that, as design engineers acquire tools that make design work more productive,

the frequency of interdepartmental reviews might need to increase, to keep distributed expertise about new product work balanced across organizational lines.

Modeling for better theories

This research demonstrates that the system dynamics method can complement theories invoking recursive dynamics by helping represent and explicate patterns in which a change in one part of a social or physical system feeds back to affect itself. In particular the system dynamics' grammar of accumulations, in-the-moment activities, and feedback is well suited to giving operational, setting-specific forms to theories of structuration (Giddens, 1984) and practice (Bourdieu, 1980/1990). These theories distinguish between enduring resources and emerging actions, while positing that agents' moves are contingent in some respects on the relative position of those resources, which enable and constrain their actions.

By constructing models of two case studies in accordance with tenets of these social and organizational theories, I built representations of the dynamics observed at the sites different from those I would have constructed had I proceeded without the guidance of these theories. (I might not have explicitly represented knowledge accumulations or represented that people in different roles and departments often learn from disparate kinds of activities.) Moreover, simulating these models helped deepen my theorizing about collaborative dynamics in a way that would not have been possible otherwise. Powerful theories about organizational dynamics, applied to specific field studies, and cast in representations that permit experimentation with circumstances and timing both observed and unobserved allow more comprehensive discussion of causality than achievable by simulation modeling uninformed by social and organizational theory or theorizing about organizational dynamics without checks for internal consistency.

Practical implications of intervening for collaboration at the boundary

Practical implications of intervening to (re-)balance expertise *across* a boundary may seem counterintuitive: We tend to assume that more expertise, wherever possible, will lead to better organizational outcomes. This research posits that less expertise can, through the process of cross-boundary interactions, lead to more desirable organizational outcomes by allowing people on either side of the boundary to recognize, explore, and learn from their interdependence in work at comparable paces.

This process, of course, takes time and investment to yield the better organizational outcome. Hiring doctors with expertise in CT and technicians inexperienced with CT probably leads to better scanning and diagnosis in the first few months after deploying the new scanning machine, even though uncollaborative patterns cause learning among the CT staff, as a whole, to plateau well below its potential. Initiating efforts to involve manufacturing and assembly in a new product effort when design engineers have not yet completed essential aspects of the design requires both design and manufacturing personnel to interrupt their respective productive activities and expend resources to portray and discuss "half-baked" work. If we have a modicum of interest in any but the shortest-term outcomes, however, we must consider effects of cross-boundary interactions and distributed organizational knowledge through time. While practitioners and scholars often emphasize the need for adequate training when introducing a new technology or process, the importance of balancing expertise *across* boundaries of role or function has received little attention. Staffing to balance relative expertise and designing cross-boundary interactions to establish comparable rates of learning merit new scrutiny.

Practitioners have reported that an organization as a whole can often react negatively to attempts to overcome traditional intra-organizational boundaries. Some have described the successful effort as an "infection," triggering the organization's "immune system," which then seeks to stamp out the invading behaviors. *Car Launch* (Roth and Kleiner, 2000), for example, describes an innovatively managed product development effort at an automotive company. It launched with far fewer defects than ever believed possible, and upon the project's completion upper management fired the project managers and refused to repeat the experiment that had led to radically improved product development practices. Similarly, one of my co-workers at Federal Express described his experience facilitating Joint Application Development (or JAD) sessions, where developers and users meet in extended workshops to specify and analyze requirements for new information systems. He told how typically adversarial relationships between development and user groups would become collaborative during the workshops, leading to path-breaking agreements for system development that would benefit all concerned. When the JAD sessions concluded, however, members of these divisions who did not participate ridiculed their co-workers who had. They actively worked to undo the emerging agreements, thereby delaying development and deployment of needed information systems, or reducing their designed capability.

The concepts put forth in this research can help explain why this phenomenon might occur—which suggests something of their power for managing cross-boundary interactions. In short, successfully navigating across one boundary creates another boundary. To elaborate, I consider the interaction across the user-developer line described by a co-worker. In a JAD session both users and developers cede control of the conversation to a facilitator, who provides a process for interacting that engages participants on both sides. It is the facilitator's work to

ensure that terms are defined in ways that both groups comprehend, that each party's jargon or shorthand is not only explained but re-cast in terms that the other party can use. In this way, the facilitator's manipulation of whiteboards, drawings, and vocabulary, as well as his management of "air time" by overly vocal or silent participants, continually rebalances parties' expertise for representing their work to others at the boundary. Thus JAD interactions allow users and developers to learn how their own work-at-hand affects and depends upon the others'. Users learn not only about their responsibilities in creating and deploying a new information system but also about capabilities and limitations of the developers and their tools. Similarly, developers learn not only about their role for creating and maintaining the new information system but also about capabilities and limitations of the users in accomplishing the company's work. With each side accumulating expertise in these ways at relatively the same rate because the facilitator keeps any one part of the group from getting ahead of the other, collaborative patterns of interaction emerge and persevere during the workshop.

When JAD participants return to their own groups, however, they have accumulated knowledge, a new understanding of their own work and the others' work, which their co-workers have not gained. New pragmatic boundaries, within divisions, have emerged. But there is no process for bringing co-workers' expertise to a level comparable to those who learned during the JAD sessions. Instead, new cross-divisional agreements emerging from the JAD workshop are announced, while uncollaborative intra-divisional patterns between JAD participants and their co-workers take hold and further prevent interactions that could shift and rebalance relative expertise across the new within-division boundary. Over time intra-divisional conflicts and misunderstandings can sabotage the cross-departmental work achieved earlier.

5.3 Current limitations and future directions of research

The research presented in this dissertation contains several limitations, each of which presents an opportunity for extending investigation to deepen our understanding of managing interdependent work across boundaries.

First, in each case I focused on the work of only two parties, one on either side of the boundary. In reality, interdependent work often involves multiple parties, and careful analysis of efforts to collaborate by three or more parties would reveal the limits of the two-party explanations offered here. Research on multiple-party collaboration should consider dyadic interdependencies among parties, as well as the desired organizational outcome's dependence on each party's work. As the number of interdependent parties increases, artifacts, actions, and locations adequate to represent all parties' practices probably grow more difficult to concoct. For three or more parties' work, devising entirely new methods for representing their work to one another may become more valuable; each party would then begin equally ignorant of tools and applications for managing the interaction at the boundary. It may be that balancing role-specific expertise across all dyadic boundaries becomes more important as the number of parties increases. Perhaps this is why green-field sites have enjoyed notable success in innovation efforts; people from multiple practices, often the top in their respective fields, gather at a location new to each of them to devise new ways of working together.

Second, I have focused on expertise as the capital most relevant to the cross-boundary interactions studied. Extending this research both conceptually and empirically to include forms of capital in addition to practical know-how could improve its generalizability. Representing influence over key resources (such as locations, machines, or funding) needed for interdependent work, for example, could extend the explanatory power of the theoretical framework in the

settings studied or ones similar. Representing accumulations of capital such as professional status or privilege resulting from gender, race, or forms of cultural distinction in extended longitudinal studies could extend the theoretical framework to explore how these slower-changing norms also nevertheless change through time, influencing (and influenced by) cross-boundary collaborations.

Third, I chose to study work across departmental and hierarchical lines, reasoning that a theory of cross-boundary collaboration must comprehend how and why we sometimes succeed and sometimes fail to surmount and transform these boundaries internal to organizations as well as explain negotiation and navigation across organizational, industrial, or national lines. I intend to expand the breadth and probe the usefulness of the theory of cross-boundary collaboration proposed here by studying inter-organizational efforts to collaborate. Research to explain successes and failures to work across boundaries signifying differences in language, law, and custom may also usefully broaden and deepen understanding of collaborative work.

Empirically, one objection to the generalizability of this work is that I have drawn conclusions from only two case studies. I propose that simulation offers a viable path for extending research on collaborating across boundaries using rich data from intensive field work. First, modeling aids in more thorough exploration and exploitation of existing data sets; I used Barley's (1986) "thick" descriptions of new scanning technology implementations, for example, to explore doctor-technician collaboration, which was not the focus of his study. Second, we can further exploit models by developing from their range of simulated behaviors propositions testable with other methods, as well as in other field settings.

The theoretical framework proposed and the setting-specific simulation analyses of two field studies have yielded explanations of patterns in cross-boundary work that contribute

theoretically and empirically to understanding the dynamics of collaboration. With increasing trends in globalization of physical resources, governmental relations, and market and financial enterprises, the ability to manage constructively interdependence across boundaries of all kinds can only grow in importance to society. While the scope of this research encompasses work across only intra-organizational lines, it provides solid steps in the direction of more comprehensive theory and practice of collaborating across all boundaries.

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