Bounded Rationality and the Search for Organizational Architecture: An Evolutionary Perspective on the Design of Organizations and Their Evolvability

Sendil K. Ethiraj
University of Michigan
Daniel Levinthal
University of Pennsylvania

We employ a computational model of organizational adaptation to answer three research questions: (1) How does the architecture or structure of complexity affect the feasibility and usefulness of boundedly rational design efforts? (2) Do efforts to adapt organizational forms complicate or complement the effectiveness of first-order change efforts? and (3) To what extent does the rate of environmental change nullify the usefulness of design efforts? We employ a computational model of organizational adaptation to examine these questions. Our results, in identifying the boundary conditions around successful design efforts, suggest that the underlying architecture of complexity of organizations, particularly the presence of hierarchy, is a critical determinant of the feasibility and effectiveness of design efforts. We also find that design efforts are generally complementary to efforts at local performance improvement and identify specific contingencies that determine the extent of complementarity. We discuss the implications of our findings for organization theory and design and the literature on modularity in products and organizations.●

Simon's (1962) work on the architecture of complexity provides the foundation for viewing organizations, as well as other systems such as products or technologies, as complex adaptive systems (Cohen and Axelrod, 1999). A central element of Simon's argument is that the fundamental features of complex systems are hierarchy, the fact that some decisions or structures provide constraints on lower-level decisions or structures, and near-decomposability, the fact that patterns of interactions among elements of a system are not diffuse but will tend to be tightly clustered into nearly isolated subsets of interactions. These dual properties of hierarchy and near-decomposability are argued to enhance the evolvability of such systems (Simon, 1962). Although hierarchy and near-decomposability may be desirable attributes of an adaptive entity, how can we presume that boundedly rational managers will be able to identify and uncover some true, latent structure of hierarchy and near-decomposability? This is a particularly important question for the growing literature on the power of modular organizational and product architectures (Sanchez and Mahoney, 1996; Baldwin and Clark, 2000), which has offered considerable insight into the power of modular designs but has left largely unaddressed the question of the feasibility of boundedly rational actors identifying more or less appropriate modular architectures.

The essential tension between designing complex systems that are hierarchical and nearly decomposable and the limits to rationality of human agents is captured in the following passage from Simon (1962: 477–478, emphasis added):

> The fact, then, that many complex systems have a nearly decomposable, hierarchic structure is a major facilitating factor enabling us to understand, to describe, and even to see such systems and their parts. Or perhaps the proposition should be put the other way round. If there are important systems in the world that are complex without being hierarchic, they may to a considerable extent escape our observation and our understanding. Analysis of their behavior would involve such detailed knowledge and calculation of the interactions of their elementary parts that it would be beyond our capaci-

0001-8392/04/4903-0404/$3.00.

●

We thank the associate editor, Reed Nelson, three anonymous referees, and seminar participants at Stanford University, Northwestern University, New York University, University of Pennsylvania, University of Michigan, the University of Michigan–Santa Fe Institute Workshop, and the Lake Arrowhead Conference on Computational Modeling in the Social Sciences for useful comments and suggestions. We also thank Linda Johanson for excellent editorial guidance. Errors and omissions remain our own.

ties of memory or computation. *I shall not try to settle which is chicken and which is egg: whether we are able to understand the world because it is hierarchic, or whether it appears hierarchic because those aspects of it which are not elude our understanding and observation.* I have already given some reasons for supposing that the former is at least half the truth—that evolving complexity would tend to be hierarchic—but it may not be the whole truth.

In the quote above, Simon raises a puzzle about the direction of causality between bounded rationality and complexity. Does bounded rationality allow us to perceive and analyze only hierarchical systems, or is it that because complex systems are hierarchical, we are able to observe and analyze them? The essential question remains: to what extent is the architecture of complexity (i.e., hierarchy and decomposability) the ultimate arbiter of feasible design efforts? This question is intimately related to a central research agenda in organization theory concerning the design of organization forms. Two contrasting themes in organization theory provide the starting point for thinking about the feasibility and value of adaptation in organizational forms themselves. Contingency arguments implicitly assume that high-level actors in an organization are able to identify and comprehend the demands imposed by their current environment and are able to design the appropriate organizational architecture to respond to those demands. The role of the manager, therefore, is to respond to the changing environment by continuously adapting to the contingencies that confront the organization (Astley and Van de Ven, 1983). The research in this tradition, however, has devoted little attention to the feasibility and efficacy of adaptation in organizational forms, focusing instead on the fit between environmental contingencies and organizational forms and the nature of the lower-order adaptation or flexibility that different organizational forms make possible.

Population ecologists (Hannan and Freeman, 1977), in contrast, argue quite explicitly about the difficulty of identifying what form may seem most apt for a particular environment or niche and, furthermore, make salient the challenges of shifting from one form to another. This perspective highlights the limits on the degree of strategic choice and the capacity of organization structures to adapt to different niches (Aldrich, 1979). Moreover, even if organizations are able to engage in adaptation of organizational forms, if the rate of environmental change is faster than the rate at which organizations can adapt their organizational forms, then such adaptation efforts are likely to be fruitless (Hannan and Freeman, 1984).

The roots of the contrasting positions of the contingency and the ecological views are embedded in both implicit and explicit assumptions about individual behavior that underpins efforts to adapt organization forms and the complexity of the challenge represented by such efforts. Because contingency theories of fit between environmental contingencies and organization design features depend crucially on the ability of managers to discover and achieve such a fit, it is important to examine whether managers, viewed more realistically as "boundedly rational," can engage in effective adaptation of organization forms to achieve such a fit with the environment. At the same time, if the relative futility of managerial action or the benefits of inertia really depend on the rate of change in the environment, then it is also useful to examine the relationship between the rate of environmental change and the effectiveness of efforts at adaptation.

A related theme, but treated largely as a distinct line of work, is the examination of first- and second-order change processes (Argyris and Schön, 1978; Bartunek, 1984; Tushman and Romanelli, 1985; Miner and Mezias, 1996). First-order change is viewed as incremental, local adaptation within a given structure (e.g., changes in pricing policies, product launches or withdrawals, changes in investments in research and development or advertising) involving the working out of specific choices within a given organizational structure. In contrast, second-order change represents change in the underlying structure itself (e.g., change from a unitary to M-form structure). Related to the prior questions of whether change in organizational forms is feasible and useful and how it is influenced by environmental change are questions related to the interrelationship between first- and second-order change processes.

The interrelationship between first-order and second-order adaptation is far from straightforward. On the one hand, because first-order adaptation is likely to yield diminishing returns as the space of possibilities within an existing organizational architecture is exhausted, a major shift in the organizational form (via second-order adaptation) may enhance the effectiveness of first-order adaptation by creating new configurations for experimentation (Levinthal, 1997), much as breakthrough innovations set the stage for subsequent refinements (Nelson and Winter, 1982). Empirical research on learning curves (Argote, Beckman, and Epple, 1990) and quality-improvement efforts support this possibility. On the other hand, aggressive second-order adaptation can undo the learning and first-order adaptations of the past, creating conditions akin to the liability of newness (Amburgey, Kelly, and Barnett, 1993). The ambiguity of predictions suggests that it is useful to examine the impact of second-order adaptation on the efficacy of first-order adaptation and the circumstances under which they are complementary or conflicting.

In this paper, we connect Simon the "system designer," who exposes the power of hierarchical and nearly decomposable systems, with Simon the forceful proponent for the notion of bounded rationality. Uniting Simon's contrasting ideas about bounded rationality and complex system design, we address three questions that speak to the literature on organization design and change processes: (1) How does the architecture or structure of complexity affect the feasibility and usefulness of boundedly rational design efforts? (2) Do efforts to adapt organizational forms complicate or complement the effectiveness of first-order change efforts? and (3) To what extent does the rate of environmental change nullify the usefulness of design efforts? In the process of addressing these questions, we hope to delineate at least a skeleton of a micro-foundation for some of the important "macro" questions about the design and evolution of organizational forms.

We examine these questions in the context of a computational model of organizational adaptation. Such a methodological approach allows us to examine the complex interaction among search processes at different levels of analysis (the space of alternative structures and the set of alternative actions) and, in a controlled manner, to consider how these processes are affected by different environmental settings and varying degrees of environmental change. As a model, by necessity, it is a stylized representation of actual processes of organizational adaptation. We build closely on prior work on models of organizational adaptation (Lant and Mezias, 1990; Levinthal, 1997) and specify a process of adaptive search for organizational form that roughly parallels these existing specifications of local search processes. Our characterization of an organizational form focuses on the segmentation or departmentalization of activity and the allocation of specific functions to a particular organizational subunit (Marengo et al., 2000; Rivkin and Siggelkow, 2003). This is not to suggest that there are not other important facets of an organization's form one might want to consider, including the informal pattern of interaction among actors or some notion of values or organizational culture. But, as Scott (1998: 26) suggested, a distinctive feature of organizations is their "relatively formalized social structures," and these features of structure on which we do focus constitute the central elements that are manipulated in the process of restructuring (Kelly and Amburgey, 1991).

COMPLEX ORGANIZATIONS AND THEIR ENVIRONMENTS

Complex Organizations and the Design Problem

Building on the work of Simon (1962: 468) and Perrow (1972), complex organizational systems can be characterized as consisting of a large number of elements that interact in a non-simple way.[1] The complexity that stems from a large number of elements interacting in non-trivial ways is twofold. First, the large number of elements creates difficulty in comprehending the structure that binds them. Second, even if one is able to uncover and comprehend the structure that binds the elements, anticipating the effects of the interactions on system behavior and performance is non-trivial (Kauffman, 1993; Cohen and Axelrod, 1999). The complexity increases as the system gets larger because designers need to first discover which elements interact with which others and then discover the nature of the interaction relationship (see Perrow, 1999, chap. 3 for a discussion). The following quote describing the complexity of Xerox's photocopiers (Adler and Borys, 1996: 68) vividly portrays the difficulty inherent in comprehending and intervening in complex structures:

> During the 1970s, Xerox photocopiers grew vastly more sophisticated in their functionality. As a result, even simple tasks such as copying, loading paper, and resupplying ink became more complex, and recovery from routine problems such as paper jams became more difficult. It became increasingly common for users to walk away from the machine rather than waste time trying to work out how to clear a paper jam or replace the ink supply. This resulted in unnecessary downtime and expensive service calls.

1
For instance, predicting system behavior is relatively easy if the interactions between the elements are linear. But if elements interact such that the relationship within and between them is non-linear, i.e., positive over some range and negative or unrelated over other ranges, then predicting system performance becomes a difficult problem.

Similarly, Chandler's (1962: 91) description of Du Pont's growing pains highlights the challenges of complexity in an organizational setting:

> The essential difficulty was that diversification greatly increased the demands on the company's administrative offices. Now the different departmental headquarters had to coordinate, appraise, and plan policies and procedures for plants, or sales offices, or purchasing agents, or technical laboratories in a number of quite different industries. . . . Coordination became more complicated because different products called for different types of standards, procedures, and policies. . . . Appraisal of departments performing in diverse fields became exceedingly complex. Interdepartmental coordination grew comparably more troublesome. The manufacturing personnel and the marketers tended to lose contact with each other and so failed to work out product improvements and modifications to meet changing demands and competitive developments. . . .

The problem of adaptive change in such settings is made even more salient, particularly if we assume that managers are boundedly rational, because any adaptive attempt is based on guesses about the nature of interactions and interaction relationships among organizational choices and decisions.

The design of complex organizations, in its simplest form, invokes two important principles: reductionism, breaking up a complex whole into simpler units, and the division of labor, grouping tasks or units based on similarity in function. The two principles serve to economize on the cognitive demands placed on the designer (Miller, 1956) and also minimize redundancies in task performance. This idea has persisted in and remained central to the ideas of more recent organization theorists, albeit under various labels, such as nearly decomposable systems (Simon, 1962), loosely coupled systems (Weick, 1976), or pooled, sequential, and reciprocal interdependence (Thompson, 1967).

Among the many coordination benefits of specialization and the division of labor, one of the most important ones from an adaptive standpoint is the potential for relatively autonomous adaptation within the specialized units or departments. This allows for localized adaptation within problematic parts of the organization, while simultaneously buffering the unaffected parts (Thompson, 1967), or engaging in parallel and simultaneous adaptive attempts in different departmental units (see Weick, 1976, for seven adaptive benefits of loose coupling).

A second basic principle for dealing with complexity is hierarchy. Specialization or the division of labor can help eliminate redundancies and duplication of effort, though the decisions or activities that are compartmentalized still may need to be coordinated. Among other roles, hierarchy serves the important function of temporally ordering activities and helps eliminate endless cycling in their performance. Simon (1962) suggested that complex systems that resemble hierarchies tend to evolve faster and toward a stable, self-reproducing form as compared with non-hierarchic systems. The property of hierarchy is argued to be found not by chance, but favored by evolutionary selection processes (Simon, 1962).

The notion of hierarchy is often used interchangeably with organizational fiat (Williamson, 1975) or authority (see Rivkin and Siggelkow, 2003, for an implementation of hierarchy as authority using a modeling structure similar to ours). Rather, in this paper, the notion of hierarchy is used in the sense of nested hierarchies (Baum and Singh, 1994) in which there is a precedence ordering of tasks or activities in the organization. In the context of organization design, the line of hierarchy denotes the flow of information, or constraints, from the immediately higher department or unit. Similarly, in an organizational context, Simon's (1957) notion of decision premises has the property of a nested set of constraints on organizational decision making. The important function of hierarchy is not only to resolve conflicts between subsystems (Thompson, 1967: 60) but also to facilitate learning through trial and error by allowing systematic and orderly local search and exploration. Hierarchy enables the recognition of progress toward one's goals and the evolution of a system through several intermediate stable configurations (Perrow, 1972: 44–52). In contrast, non-hierarchic systems, which display no particular order in their configuration, make local search and trial-and-error learning much more difficult to accomplish.

Interestingly, Xerox's response (Adler and Borys, 1996) to the growing complexity of its copiers and that of Du Pont to its diversification (Chandler, 1962) was to redesign their product and organization, respectively, conforming to the twin principles of decomposability and hierarchy:

> Through its physical structure and the displays it offered, the machine provided a succession of informative views of the copier's functioning and of the user's interaction with it at various stages of the copying experience. As the views unfolded, they helped users form mental models of the machine's subsystems and of the experience of interacting with those subsystems. The views included step-by-step presentations of machine subsystems, their functions, and the corresponding task sequences. The views supported copying tasks by talking the users through them—neither concealing information nor overloading users with incomprehensible or unrelated information. The interiors, for example, were designed to express various layers and degrees of interaction to users and service people. The user-accessible components of the interiors (such as paper loading, jam clearing, and simple maintenance) were placed in the foreground of the visual field, and the technician-accessible components of the interior (for more complex maintenance and repairs) were placed in receding layers in the background. (Adler and Borys, 1996: 68–69)

> No member of the Executive Committee should have direct individual authority or responsibility which he would have if he was in charge of one or more functional activities of the Company. . . . For example, our plan provides that one member of the Executive Committee, who may be best fitted by experience for his duty, will coordinate the sales function by holding regular meetings with appropriate representatives of the five Industrial Departments. . . . According to this plan, the head of each Industrial Department will have full authority and responsibility for the operation of his industry, subject only to the authority of the Executive Committee as a whole. He will have under him men who will exercise all the line functions necessary for a complete industry, including routine and special purchasing, manufacture, sales, minor construction. . . . (Chandler, 1962: 107)

The description of the copier redesign effort and the restructuring of Du Pont invoke the twin principles of complex system architecture advocated by Simon (1962). The design of the copier into subsystems and concealing irrelevant information within modules or subsystems (Baldwin and Clark, 2000) corresponds to near decomposability or the loose coupling of structural elements. Similarly, identifying task sequences and separating the various layers and degrees of interaction is consistent with the principle of hierarchy. By the same token, the creation of multiple, autonomous divisions in Du Pont corresponds to the principle of decomposability, i.e., grouping of activities that are strongly interdependent, whereas the members of the Executive Committee approximate the principle of hierarchy in achieving coordination when interdepartmental interdependence was involved. While the flexibility and coordination benefits of design architectures that are hierarchical and nearly decomposable are widely reported in the literature (Lawrence and Lorsch, 1967; Adler, Goldoftas, and Levine, 1999; Baldwin and Clark, 2000), how one discovers or designs such an architecture for a complex product or organization is relatively underexplored. The design challenge is compounded when we consider not omniscient designers but boundedly rational designers engaging in local and imperfect search in the space of design possibilities. Does the tractability of the design challenge for boundedly rational agents vary with the underlying architecture of the complex problem? We explore this complex design challenge in a setting in which there is an explicit recognition of the limits to the adaptive and inferential capacity of the design effort.

Contingent Logic of Alternative Environments

As suggested above, we focus on two aspects of organization design: (1) how to group organizational functions into two or more departments or units and (2) specify the hierarchy of information flow or task ordering between the departments. As a result, the critical feature of the environment from the perspective of our analysis is the net effect of task, technology, and institutions on the choices of the number and nature of departments and the information flow between them. Consistent with contingency logic, there should be some ordering among the set of possible organizational forms based on their fit with a given set of environmental conditions—different groupings of organizational choices and the direction of information flow among them will vary in their efficacy, depending on the myriad environmental influences at work.

Accepting the existence of some inherent contingency logic about the desirability of alternative forms, if managers make guesses about structures and observe the consequences of their choices, it is reasonable to expect to observe (boundedly rational) efforts at adaptive organizational change. For instance, if a multinational corporation (MNC) operating in different countries all over the world employs a functional structure to coordinate its activities and observes the dysfunctional effects of the uniformity of policies in different countries, such information constitutes feedback about the inappropriate grouping of organizational choices and functions. It is reasonable to expect the managers of the MNC to engage in efforts to adapt the organization structure in the light of such feedback. While bounded rationality suggests that they are unlikely to discover the appropriate structure in the first attempt, it is certainly possible that repeated, small adaptive attempts will generate progress toward the appropriate structure.

There is, however, a second complication. The adaptive walk toward discovering the appropriate structure of a complex organization, given its environment, is likely to be relatively effective only if the environment is itself stationary. Over time, the MNC might enter or exit from different technologies, countries, and businesses, making the appropriate structure defined by the environment a moving target. What constituted an appropriate grouping of organizational functions at one time might be inappropriate at another time. This brings us back to the central questions posed in this paper. Can boundedly rational managers of complex organizations engage in effective design of organizational forms given that the environment that defines the appropriate organizational form is itself changing?

First-order and Second-order Adaptation

The roots of the distinction between first-order and second-order change processes can be traced to Argyris and Schön (1978). First-order adaptation occurs within the parameters of an existing architecture or design and is geared to improving performance and finding durable fixes and solutions to identified problems (Bartunek, 1984). For instance, in the photocopier example, first-order adaptation would involve incremental tweaks to the design, such as making it easier to open a door to remove paper jams or load paper. Such incremental changes are a result of cumulative learning by doing over long periods of time (Nelson and Winter, 1982; Adler and Clark, 1991). In contrast, second-order adaptation involves a change in the existing architecture itself. Thus, fundamental shifts in strategy or structure would fall within the ambit of second-order change (Bartunek, 1984). Analogously, adaptation of organizational forms or designs is akin to second-order adaptation, whereas incremental adaptation within a given organizational form is akin to first-order adaptation (Fiol and Lyles, 1985). The obvious downside risk of second-order adaptation is the obliteration of prior first-order adaptation efforts (Tushman and Romanelli, 1985). For instance, with a complete redesign of the architecture of the copier, the difficulty of retaining all the incremental first-order adaptive efforts of the past is quite apparent. Often, realizing the full benefits of second-order adaptation requires the elimination of prior first-order adaptations.

On the upside, second-order adaptation can open up new opportunities for successful first-order adaptation efforts because opportunities for first-order adaptation often exhibit diminishing returns over time. In complex interdependent systems, first-order adaptation efforts are rarely costless. Improvement in one dimension often comes at the cost of deterioration in one or more other dimensions. As more and more such adaptations are carried out, the available opportunities for productive adaptation decline over time (Tushman and Anderson, 1986). In such cases, a change in the architecture or second-order adaptation can create new opportunities for first-order adaptation (Henderson and Clark, 1990).

The preceding discussion hints at a trade-off between first-order and second-order adaptation. But what is unclear is the precise nature of the trade-off. The empirical literature in organization theory remains inconclusive. Carroll and Hannan (2000: 371) presented a list of 15 papers in organization theory, with eleven studies finding a positive relationship between organizational change and mortality and eight (some studies show both findings) studies documenting a negative relationship. Carroll and Hannan (2000) suggested that changes in core aspects of organizations are likely to threaten survival, while incremental and peripheral changes are likely to be less disruptive. As a field, however, we need greater conceptual clarity as to what constitutes core versus peripheral changes. As an initial step in this direction, we examine the boundary conditions under which first-order and second-order adaptations are complements and the conditions under which they counteract each other.

We seek therefore to investigate three distinct but interrelated questions that constitute the foundational structure of organization theory: (1) How does the architecture or structure of complexity affect the feasibility and usefulness of boundedly rational design efforts? (2) To what extent does the rate of environmental change nullify the usefulness of design efforts? and (3) How does second-order adaptation—design efforts—affect first-order adaptation—incremental performance improvement efforts? The first question speaks to the fundamental dilemma of causality between bounded rationality and complexity posed by Simon (1962). The next two questions examine how our understanding of environmental change and organizational adaptation processes tempers the practical usefulness of design efforts. In other words, does the primacy of environmental and organizational change processes overwhelm the feasibility and/or functionality of organization design efforts? We set up a formal modeling structure to explore the research questions outlined above.[2]

MODEL

The first question was how the architecture of complexity affects the feasibility and usefulness of boundedly rational design efforts. In addressing this question, we sought to hold constant the boundedly rational nature of the search processes and show the relative effectiveness of this search process as the architecture of complexity varies. Toward this end, we set up four alternative states of the world (what we term generative structures from here on) that vary in the nature of the underlying complexity discussed above—decomposability and hierarchy: (1) hierarchical and loosely coupled (figure 1a); (2) non-hierarchical and loosely coupled (figure 1b); (3) hierarchical and tightly coupled (figure 1c); and (4) non-hierarchical and tightly coupled (figure 1d).[3] In the figures, an alphanumeric notation represents each decision variable. The alphabetic portion denotes the department, while the numeric portion denotes the respective decision choice. The x's in each

2
In the interest of readability, details of the formal implementation are provided in the Appendix.

3
Note that figures 1a–1d bear a resemblance to two recent published papers (Rivkin and Siggelkow, 2003; Ethiraj and Levinthal, 2004). The similarity is a function of the common modeling apparatus employed. The research questions examined here, however, share no overlap with the research questions of either of those two papers.

Figure 1a. Hierarchical and loosely coupled.

	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	c_1	c_2	c_3	c_4
a_1		x	x	x								
a_2	x		x	x								
a_3	x	x		x								
a_4	x	x	x									
b_1						x	x	x				
b_2	x				x		x	x				
b_3		x			x	x		x				
b_4					x	x	x					
c_1								x		x	x	x
c_2									x		x	x
c_3									x	x		x
c_4							x		x	x	x	

Figure 1b. Non-hierarchical and loosely coupled.

	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	c_1	c_2	c_3	c_4
a_1		x	x	x								
a_2	x		x	x			x					
a_3	x	x		x								
a_4	x	x	x									
b_1						x	x	x				
b_2					x		x	x				
b_3		x			x	x		x				x
b_4					x	x	x					
c_1										x	x	x
c_2									x		x	x
c_3									x	x		x
c_4							x		x	x	x	

row-column intersection identify interdependence between decision choices. Reading across a row, an x indicates that the row variable is affected by the column variable. Conversely, reading down a column, an x indicates that the column variable affects the row variable. Therefore, x's positioned symmetrically above and below the principal diagonal represent reciprocal interdependence between decision choices.

Within each department, each decision choice is tightly coupled with other decision choices in the same department, what Thompson (1967) termed reciprocal dependence. Figure 1a depicts a structure that is hierarchical and loosely coupled, i.e., departments 2 and 3 have a weakly coupled relationship with the next higher department, denoted by a single x below the principal diagonal. The presence (or

Figure 1c. Hierarchical and tightly coupled.

	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	c_1	c_2	c_3	c_4
a_1		x	x	x								
a_2	x		x	x								
a_3	x	x		x								
a_4	x	x	x									
b_1	x	x	x	x		x	x	x				
b_2	x	x	x	x	x		x	x				
b_3	x	x	x	x	x	x		x				
b_4	x	x	x	x	x	x	x					
c_1					x	x	x	x		x	x	x
c_2					x	x	x	x	x		x	x
c_3					x	x	x	x	x	x		x
c_4					x	x	x	x	x	x	x	

Figure 1d. Non-hierarchical and tightly coupled.

	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	c_1	c_2	c_3	c_4
a_1		x	x	x	x		x					
a_2	x		x	x	x	x		x				
a_3	x	x		x		x	x	x				
a_4	x	x	x		x		x					
b_1	x	x		x		x	x	x	x	x		x
b_2		x	x		x		x	x	x		x	
b_3	x		x	x	x	x		x	x	x		x
b_4		x	x		x	x	x			x	x	
c_1					x	x	x			x	x	x
c_2					x		x	x	x		x	x
c_3						x		x	x	x		x
c_4					x		x		x	x	x	

absence) of hierarchy is identified by the asymmetry (or symmetry) in between-department interaction. The degree of loose coupling is a function of the strength (i.e., magnitude) of between-department interactions. If there are no interactions between departments, then the organization is fully decoupled. In figure 1a, decision a_2 influences the payoff associated with decision b_3. This also corresponds to sequential or hierarchical interdependence between departments (Thompson, 1967).

Figure 1b denotes a loosely coupled but non-hierarchical structure. The structure is still loosely coupled, because the interaction within departments is stronger than the interaction between departments, but the structure is not hierarchical, because there is no precedence ordering of activities between the departments. Departments a and b are characterized by reciprocal interdependence (Thompson, 1967) and symmetry in between-department interactions. Figure 1c describes a hierarchical but tightly coupled structure. The interaction between departments a and b and departments b and c is as strong as the interaction within the respective departments. In this organization, however, hierarchy is preserved because there is only sequential interdependence between departments, i.e., department a affects department b, but not vice versa. Finally, figure 1d represents a non-hierarchical and tightly coupled structure. In the four settings, the degree of coupling in figure 1a and figure 1b (and figures 1c and 1d, respectively) is held constant, as the total number of interactions off the principal diagonal is equal.

Each of the four structures, in a stylized manner, represents different contexts that managers encounter. For instance, the hierarchical and loosely coupled structure might characterize the relationship between the research and development (R&D) and manufacturing departments of a pharmaceutical company. The process of drug discovery, including drug development and clinical trials usually spans between 3.5 and 13 years (Dranove and Meltzer, 1994). Moreover, because the Food and Drug Administration (FDA) approval rate for new drugs is only about 17–20 percent (DiMasi, 2001), it is likely that the R&D process is highly decoupled from the manufacturing process, with the latter emerging as a significant issue only after the FDA's approval of the drug. This suggests that figure 1a might be representative of the hierarchical and loosely coupled relationship between R&D and manufacturing in pharmaceutical firms.[4] In more process-intensive industries such as chemicals and semiconductors, however, it is likely that manufacturing considerations will be tightly coupled with R&D decisions (Ulrich and Eppinger, 1999: 20). This leads us to expect that the R&D-manufacturing relationship in the semiconductor industry is likely to be non-hierarchical and tightly coupled, as in figure 1d.

Both situations are in contrast to a case in which the relationship between R&D and manufacturing is loosely coupled but mutually consultative in nature (i.e., figure 1b), i.e., R&D iterates its designs based on input from manufacturing. This is likely to be the case in the automotive industry, though the strength of the relationship likely depends on the extent to which manufacturing-cost considerations dominate (Clark and Fujimoto, 1991). Lastly, the relationship between R&D and manufacturing in the biotechnology industry seems representative of the hierarchical and tightly coupled structure. A biotechnology product is a protein-based drug, in contrast to a pharmaceutical product, which is chemical-based. Protein-based drugs are derived from living organisms, human blood and plasma, and proteins. As a result, the manufacturing process cannot be divorced from product-development R&D. Thus the separation between R&D and manufacturing that exists in chemical-based drugs is not possible in protein-based drugs (Dove, 2001) and leads us to expect that the R&D-manufacturing relationship in the latter will be hierarchical but tightly coupled, as in figure 1c. The descriptions of the four contrasting contexts of the R&D-manufacturing relationship suggest that the four structures might depict alternative

4
In the pharmaceutical example there is a temporal separation between R&D and manufacturing. The meaning of hierarchy in our models is simply the unidirectional flow of decision constraints. Such a unidirectional flow may be a result of the temporal separation of decisions (as in the pharmaceutical example) or simply the ordering of decision constraints between sets of activities at a point in time (see Cusumano and Selby, 1998, for an example of how Microsoft partitions its decision constraints in organizing its software development activity).

states of the world, each of which might pose different design and coordination challenges.

Addressing the three research questions posed earlier requires specifying the following: (1) the four generative structures, (2) boundedly rational second-order adaptation, (3) boundedly rational first-order adaptation, (4) environmental change, and (5) selection. The following subsections provide an intuitive explanation for the modeled processes. The Appendix provides a formal description.

Modeling the Generative Structures

We represent an organization as a set of N decision variables, some subset of which is interdependent. For simplicity and without loss of generality, each decision variable in our model is assumed to take on two possible values (0,1). Thus, the space of possible organizational action consists of 2^N possible sets of behaviors. For instance, if we consider the manufacturing strategy of a business firm, then a setting of 1 might represent a policy of outsourcing production activity, and a setting of 0 might connote engaging in in-house manufacturing. It follows that different settings for the decision variables of the organization have different performance implications. Choices about production are likely to have interactions with the investments in information technology, rate of product introductions, and so on. For instance, it is conceivable that rapid and highly variable patterns of product introductions may enhance the value of outsourcing and of a sophisticated information-technology system that can link retail activity to external suppliers. In other words, some combinations of decision choices may yield performance improvements while others may undermine it (Macduffie, 1995).

The performance of the organization ultimately depends on the settings (1s or 0s) of the decision variables, but the ability of the organization to engage in effective first-order adaptation and identify a more or less desirable set of choices is, in turn, a function of the organization's structure, in particular, the set of interactions among the decision choices, as described by figures 1a–1d. When there are no interactions between decision variables, each decision makes an independent contribution to organizational performance. As the interactions between decision variables increase, the contribution of each decision variable to organizational performance becomes increasingly interdependent. Overall performance is an average of the performance contribution of individual decision variables.

In modeling the four generative structures, there are both systematic and stochastic manifestations of each structure. First, the number of departments, D, was specified subject to the constraint that each department contained an equal number of decision choices. This was done so as to reduce the combinatorics of the possible structures we need to consider as we vary N and D. In specifying the interaction structure across decision variables, we assume that, as depicted in figures 1a–1d, all decisions within a department interact with one another. Further, for the loosely coupled structures, we assume that the number of cross-departmental interactions is 2(D-1), or, on average, two interactions between each pair of departments. For the tightly coupled structures, we assume that the number of interactions across departments is 2(N/D * N/D), or half the degree of within-department interactions. Although the magnitude of the degree of interactions is specified in this manner, the particular variables that interact with one another are chosen randomly.[5] Thus, overall interdependence in figures 1a and 1b (the loosely coupled structures) is always equal, with hierarchical and non-hierarchical structures having the same total number of between-department interactions. Similarly, for the two tightly coupled structures (figures 1c and 1d), the total magnitude of between-department interactions is the same.

Modeling Boundedly Rational Second-order Adaptation

We assume that managers make two organization design choices: (1) how many departments or units to create and (2) the assignment of functions to departments. We model an evolutionary search process wherein managers engage in boundedly rational adaptive attempts to discover superior structures, as defined by the appropriate number of departments and the appropriate mapping of decision variables to departments in the context of one of the four underlying generative structures. We implement three search operators that collectively represent second-order adaptation: (1) splitting, (2) combining, and (3) reallocation.

Splitting may be seen as the breaking up of existing departments into two or more new departments. As departments in organizations grow larger, the same piece of information is likely to have to pass through a larger number of potentially redundant individuals before resulting in an action or decision. In such cases, splitting an existing department can help economize on information flow (Arrow, 1974). Splitting is also necessitated when a department is engaged in a number of unrelated activities, each of which requires different skills, people, and/or resources. In such settings, splitting facilitates differentiation (Lawrence and Lorsch, 1967) among organizational units to allow specialization to their specific contexts.

Combining is the opposite of splitting, akin to combining or integrating two or more departments. From the seminal work of Lawrence and Lorsch (1967), we know that organizational structures are constantly balancing the contrasting forces of differentiation and integration. While pressures for local adaptation dictate greater differentiation, the pressures for broader efficiencies in organizational performance demand greater integration. Empirical evidence shows that organizations often cycle between extended periods of increasing decentralization (differentiation) and increasing centralization (integration) (Mintzberg, 1979; Cummings, 1995; Nickerson and Zenger, 2002), suggesting that the combining operator might be an important counterpart to splitting.

In reallocation, organizations transfer or reassign functions from one subunit to another. Such reorganization does not lead to more (as in splitting) or less (as in combining) partitioning of tasks but simply involves the reallocation or reassignment of functions between departments. For instance, the shift from an organization structured along geographic lines to a product structure (Bartlett and Ghoshal, 1989) or

5
We did robustness checks (available on request) that vary the degree of within-department interactions and the treatment of loosely versus tightly coupled structures. In the loosely coupled structure, the qualitative results hold as long as the intensity of interactions within departments is greater than the intensity of interactions between departments. Correspondingly, in tightly coupled structures, the qualitative results hold as long as the intensity of interactions across departments is greater than or equal to the intensity of interactions within departments.

from a functional structure to a product structure (Chandler, 1962) has no clear implication for the number of subunits but obviously would involve the wholesale reconfiguration of organizational activity.[6] Collectively, these operations of combining, splitting, and transfer are the mechanisms that generate change in both the number of departments within the organization and the assignment of decision variables to departments, what we consider to be an organization's architecture.

The inference involved in the three operations is boundedly rational. Managers employ the operations of splitting, combining, or transfer based on their understanding of whether one or more decision choices belong to their respective department. The inferential process is imperfect in that only pairs of departments are compared at a time, and the examination of each department is only local. As a result, the eventual outcome of the attempts at redesign is not always functional from the organizational standpoint, thus rendering second-order adaptation imperfect. In addition, observing such patterns of influence does not assume that managers understand cause-and-effect processes at the department level. The only behavioral assumption made is that the designers are able to observe the effect of their actions through a crude form of root-cause analysis (Macduffie, 1997). The formal specification of the splitting, combining, and transfer operators is provided in the Appendix.

Modeling Boundedly Rational First-order Adaptation

First-order adaptation is implemented as follows. In each period of the experiment, the actors in each department attempt to enhance the performance of their particular department. Actors are assumed to "see" the performance of their given department and can anticipate what incremental changes from the existing decision string would imply for department performance. Thus adaptation occurs through a process of off-line, local search implemented simultaneously in each of the departments (cf. Marengo et al., 2000; Rivkin and Siggelkow, 2003).[7] Within each department, a decision choice is selected at random, and actors within each department evaluate the efficacy of flipping the decision choice (0,1) by the criterion of improvement in department performance. The change is implemented if there is a perceived increase in department performance. Because these change attempts occur in parallel in each of the departments, however, and the departments may have some degree of interdependence, there is no presumption that these change efforts will in fact improve organizational performance, or even department performance.

Modeling Environmental Change

Environmental change, according to the contingency view, causes misalignment of organizational structures, choices, and environmental demands. As described above, managers engage in second-order adaptation to align the organization structure with the unknown generative structure. A change in the environment will have at least two effects on organizations. First, environmental change can obviate prior first-order

6
In the context of the splitting and combining operators, we considered substantial, discrete points of restructuring. With respect to the transfer of activities, we examined reallocation of individual elements from one subunit to another, or what Eisenhardt and Brown (1999) referred to as a form of "patching." Over time, such incremental efforts at reorganization can cumulate in broad changes.

7
This capability, as suggested by Rivkin and Siggelkow (2003), may be a function of effective accounting systems that can facilitate the evaluation of department-level performance. Indeed, activity-based costing is widely deployed to track the performance of organizational subunits (Cooper and Kaplan, 1992).

adaptations, and in that sense, environmental change can be competence destroying (Tushman and Anderson, 1986). Second, environmental change may render less appropriate a given organizational form (Stinchcombe, 1965). For instance, in a multinational firm, if political change in the host country in which the firm operates increases the asset expropriation threat, then the old policies that guide investment and growth are unlikely to remain relevant. The organization's managers now need to balance the pursuit of growth against the threat of expropriation.

To capture the effects of the possible obsolescence of organizational competence, as expressed in the reduced performance associated with the current set of policy choices, and the possible misalignment between environmental demands and the organization structure, we allow the environment to change every period with some probability, Δ. A stable environment is specified as $\Delta = 0$, and the environment changes every period with certainty when $\Delta = 1$. For all intermediate values of Δ, the environment changes probabilistically.

Specifically, following each environmental change, we respecify the coupling of decision variables within departments and the nature of between-department interactions that make up the generative structure. Contrasting figure 1a with figure 1e illustrates the effect of environmental change for the hierarchical and loosely coupled structure. Two changes are visible in a comparison of the two figures. First, the composition of the departments is altered in the sense that decision variables subscripted a, b, and c are no longer clustered together in the same department. Second, the between-department interactions are altered as well. We implemented environmental change in the three other structures along similar lines.[8] Given the newly specified structure, the performance landscape is re-seeded to generate a new mapping between decision variables and performance outcomes. The form of environmental change we implement

Figure 1e. Hierarchical and loosely coupled structure after environmental change.

	a_1	a_2	b_4	c_2	a_3	b_1	b_3	c_1	a_4	b_2	c_3	c_4
a_1		x	x	x								
a_2	x		x	x								
b_4	x	x		x								
c_2	x	x	x									
a_3						x	x	x				
b_1	x				x		x	x				
b_3		x			x	x		x				
c_1					x	x	x					
a_4								x		x	x	x
b_2									x		x	x
c_3									x	x		x
c_4							x		x	x	x	

8
We also implemented environmental change as also triggering a change in the number of departments that represent the generative structures. The results were identical and are available from the authors on request.

is best described as radical in the sense that all prior adaptations and learning are destroyed after the environmental change, which we recognize may be quite rare. Change is more often incremental and tends to devalue some prior adaptations while preserving others. We are interested, however, in assessing the usefulness of second-order adaptation in the context in which it is most favorable. If inert structures are shown to outperform those that undergo second-order change in such settings, then clearly inertia with respect to form will prevail in settings with less radical change. We recognize, however, that as one moves along the continuum from a stable to a radically changing environment, the value of second-order change efforts changes commensurately.

Modeling Selection

Organizational selection processes are modeled as being proportionate to fitness. The probability that an organization will be selected equals its performance level divided by the sum of the performance of all organizations in the population at that time. This is a standard assumption in modeling biological processes (Wilson and Bossert, 1971) and has been used in a number of models of organizational selection (see Lant and Mezias, 1990, 1992; Levinthal, 1997).

ANALYSIS

For each run of the model, a generative structure is specified as described above. In addition to initializing the performance landscape, we drew the states (0,1) of the vector of decision choices at random at the start of an experiment. Because any single run is sensitive to the inherent randomness in both the initial states of the decision choices and the performance landscape, we replicated each experiment 100 times with different starting seeds for both the specification of the performance landscape and the starting state of the system. The reported results, unless mentioned otherwise, are averaged over the 100 runs to remove the stochastic component endemic to any single run. Figure 1f illustrates an interaction matrix for a single organization at the start of a typical experiment. As can be seen from the figure, the starting organization design contains unequal-sized departments with no systematic pattern of interactions among decision choices. In each run, we generate 100 organizations in which for each organization, the number of departments and the allocation of activities to departments is randomly specified, as are the settings for the decision choices. Thus at the start of each run, there are typically 100 different organizational forms, each of which independently engages in second-order adaptation.

The Architecture of Complexity and the Effectiveness of Design Efforts

The first experiment was designed to answer the question of how the architecture of complexity affects the feasibility and usefulness of boundedly rational design efforts (i.e., second-order adaptation). The second-order adaptation challenge entails discovering the set of interactions among the N decision variables and clustering those decision variables that seem to have strong interactions with each other. We exam-

Figure 1f. Typical perceived interaction matrix of decision choices at the start of the experiment.

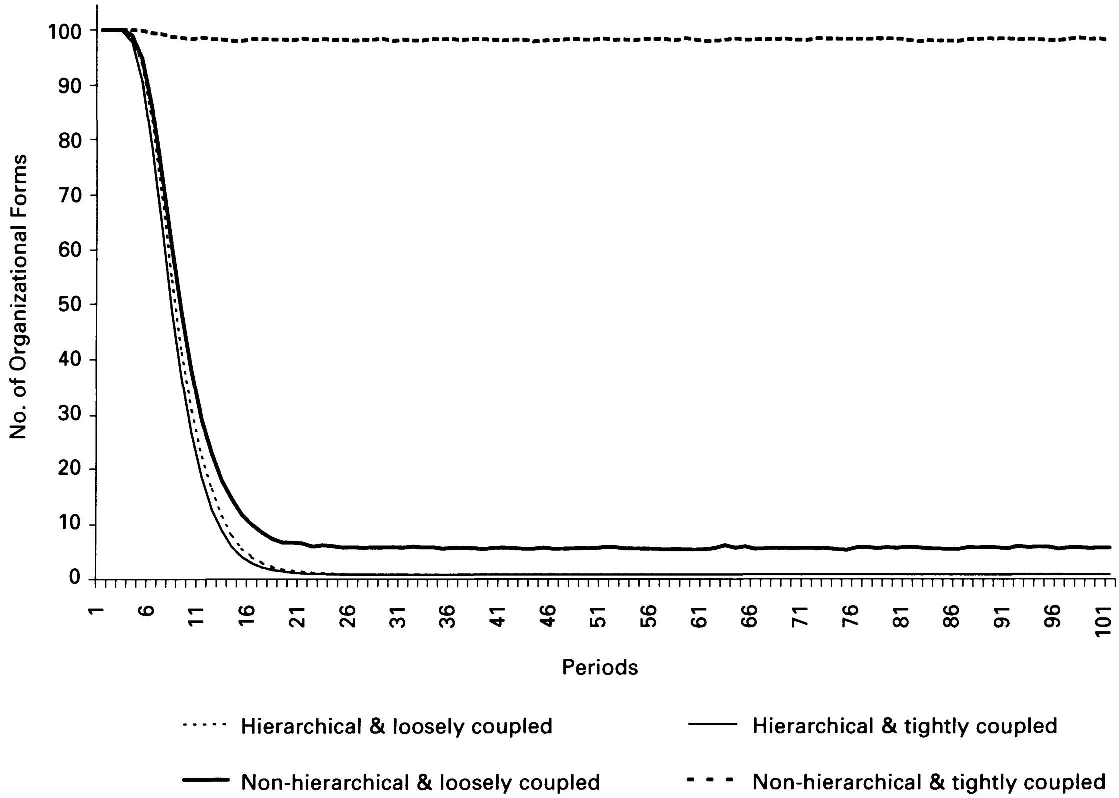
	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	c_1	c_2	c_3	c_4
a_1				x								
a_2							x					x
a_3					x				x	x	x	
a_4	x											
b_1			x						x	x	x	
b_2								x				
b_3		x										x
b_4						x						
c_1			x		x					x	x	
c_2			x		x				x		x	
c_3			x		x				x	x		
c_4		x					x					

ined whether the problem of second-order adaptation is tractable and whether and how it varies systematically with the architecture of complexity.

A key performance variable is the number of organizational forms as the simulation progresses. If second-order adaptation is fully successful, then the number of organizational forms would converge to one, i.e., the generative structure that represents the correct number of departments and the correct mapping of decision choices to the departments. This is an important performance metric because, as Simon (1962) pointed out, an important goal of organization design is to reach evolutionary stability. In the absence of any degree of stability, the efficacy of adaptation efforts is impaired.

Figure 2 plots the number of organizational forms (averaged over 100 runs) as the simulation progressed in each of the four generative structures. The figure shows that as long as the structure is hierarchical, even at extreme levels of tight coupling (figure 1c), when all decision choices of one department affect all decision choices of the immediately succeeding department (i.e., all decision choices of department 1 affect all decision choices of department 2 and so on), the process of second-order adaptation is always able to arrive at and stabilize on the corresponding generative structure used to generate the performance landscape. In contrast, when we introduced reciprocal interaction between departments, i.e., the generative structure is non-hierarchical (figures 1b and 1d), organizations never manage to reach a stable state. In the non-hierarchical and loosely coupled structure (figure 1b), organizations converge on the generative structure most of the time, but the violation of hierarchy triggers instability with about six different organizational forms continuing to survive even at the end of the experiment. In the case of the non-hierarchical and tightly coupled structure (figure 1d), the

Figure 2. Second-order adaptation in a stable environment (D = 5 and N = 30; 100 firms, 100 runs).



violation of both principles (hierarchy and loose coupling) results in the generative structure never being identified. The initial diversity of organizational forms continues to be preserved, suggesting that second-order adaptation is relatively ineffective.

We examined the sensitivity of the results in figure 2 to changes in the size of the organization (N) and the number of underlying departments (D). We found that the results are robust to changes in both the size of the organization and the number of underlying departments.[9] We observed an approximately linear positive relationship between organization size and the time periods to converge on the generative structure.[10]

The Impact of Environmental Change on Design Efforts

The previous section showed that managers were able to successfully converge on the underlying generative structure when such structures were hierarchical. These results were observed in a stable environment, but environments are rarely stable over long periods of time and, as a result, the question arises as to whether second-order adaptation efforts continue to be effective when the environment changes periodically. We reran the models presented above, introducing environmental change every period with a probability of Δ = 0.05, (implementing environmental change as described above).

The results with environmental change are presented in figure 3. Whenever environmental change occurs, the cumula-

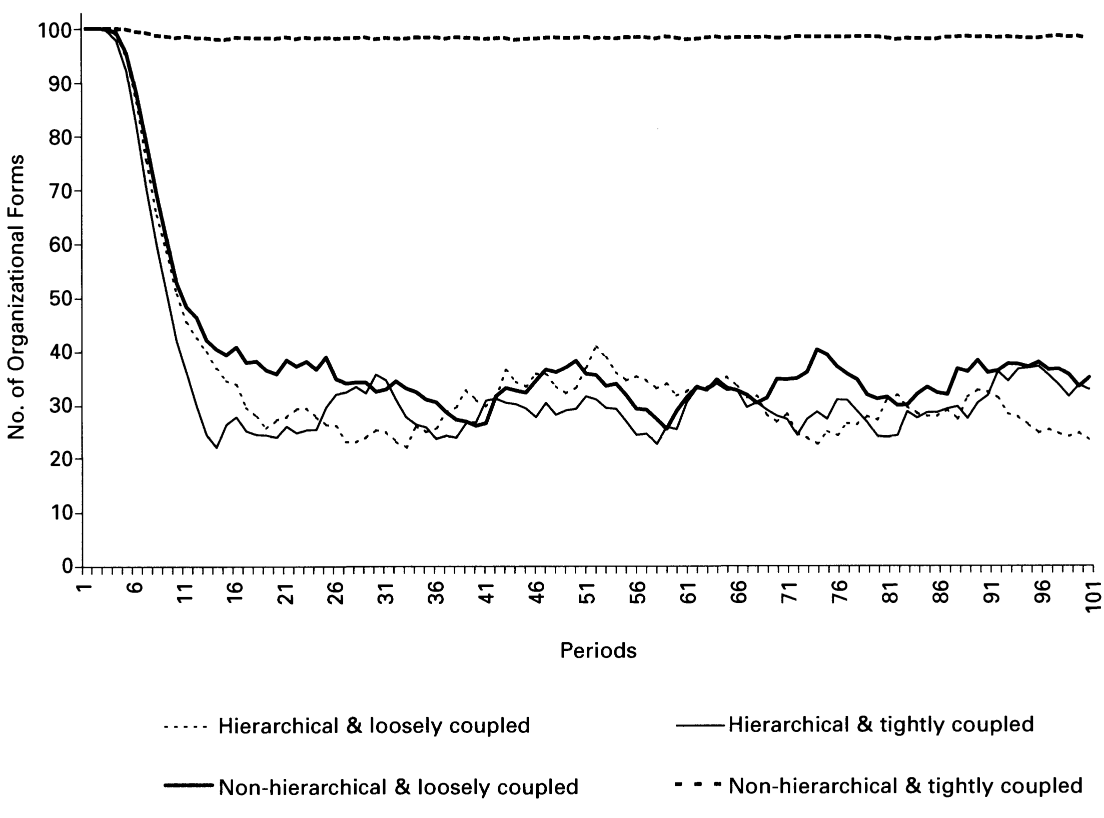
9
These results are not included due to space constraints but are available from the authors.

10
In sharp contrast, Schaefer (1999) found that, in general, with a randomly specified structure, the problem of identifying the correct modularization of an organizational (or product) design is NP-complete (Garey and Johnson, 1990).

tive adaptations of the previous periods are rendered ineffective, and the organization designs are no longer aligned with the changed generative structure. The second-order adaptation efforts of the past are effectively reset and the process begins again. The figure shows that the effectiveness of second-order adaptation in the presence of environmental change is considerably reduced. About 25–35 organizational forms continue to survive in both the loosely coupled structures (both with and without hierarchy) and the hierarchical and tightly coupled structure. The non-hierarchical and tightly coupled structure, as in the stable environment, makes the least progress in the process of second-order adaptation and, in this case, the initial diversity of organizational forms continues to persist.

The pattern of results suggests that the effectiveness of second-order adaptation in the presence of environmental change is likely to be sensitive to two parameter settings of the model. First, the frequency of environmental change is critical to the effectiveness of second-order adaptation. As the rate of environmental change increases, the process of second-order adaptation becomes relatively ineffective. More subtly, the size of the organization is also critical to the effectiveness of second-order adaptation. As observed in the previous section, there is a linear positive relationship between the size of the organization and the time periods for the second-order adaptation process to be effective. Thus, if the environment changes faster than the time it takes for second-order adaptation to work, we can expect such efforts to be

Figure 3. Second-order adaptation in a changing environment (D = 5, N = 30, Δ = .05; 100 firms, 100 runs).



futile. For instance, we ran a set of models setting N = 60 and the probability of environmental change at 0.20 and found that, on average, the initial population of 100 organizational forms reduced to only about 50, even for hierarchical generative structures. Similarly, as the radicality of environmental change declines, the efficacy of second-order adaptation efforts correspondingly improves.

The experiment shows that the process of second-order adaptation is effective when there is a hierarchical precedence structure underlying between-department interactions and the pace of environmental change is moderate. Deviations from hierarchy lead to a complete collapse of the effectiveness of second-order adaptation for tightly coupled structures. This finding regarding hierarchy formalizes Simon's (1962) intuition that complex systems that are hierarchical tend to evolve faster and toward more stable structures. Hierarchy appears to be a necessary and sufficient condition for successful second-order adaptation. Nevertheless, as a practical matter, second-order adaptation is reasonably successful even when the generative structure is not hierarchical but is loosely coupled. With a loosely coupled structure, even when hierarchy is violated, the set of organizational forms reduces to a modest number (about 6 in the stable environment and about 30 in a changing environment). In contrast, the search process is less effective when the generative structure violates both hierarchy and loose coupling.

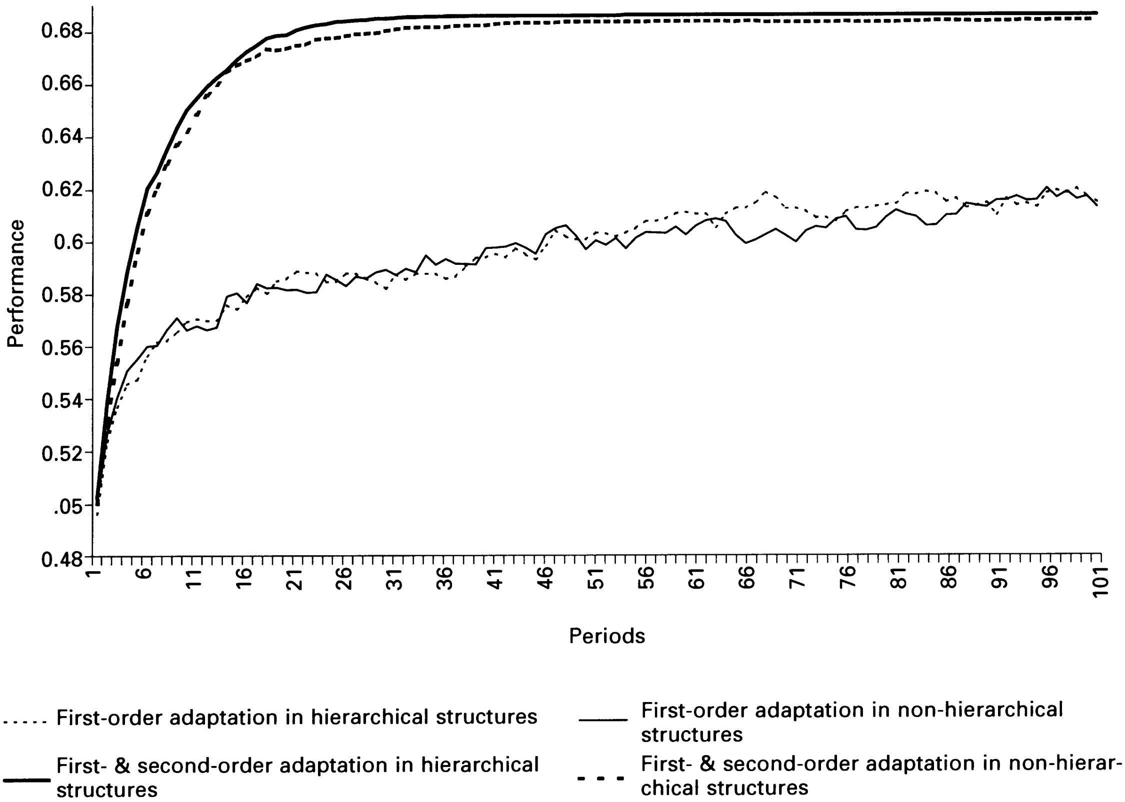
Apart from the diversity of organizational forms that are present, there is the important question of the degree of equifinality among these forms. Even if efforts at adaptive second-order change prove unsuccessful or lead to fixation on a structure inconsistent with the generative structure, this need not imply that such organizations will fail to engage in effective first-order change.

Interaction between First-order and Second-order Adaptation

As highlighted earlier, the extant literature on organization design offers ambiguous predictions about the relationship between first-order and second-order adaptation in complex organizations. The conditions under which they are substitutes and/or complements are unclear. The set of experiments reported in this section is designed to clarify the interaction relationship between first-order and second-order adaptation efforts.

Adaptation in loosely coupled structures. To explore the interaction between first-order and second-order adaptation, we preserved the process of second-order adaptation as implemented in experiment 1. In addition, we included the process of first-order adaptation. Figure 4 plots the average performance results from 100 runs of four models in which the generative structure was loosely coupled, both with and without hierarchy (i.e., figures 1a–1b) with an underlying structure of five departments (N = 30). In two of the settings, there is a simultaneous process of first-order and second-order adaptation. In the other two settings, only first-order adaptation occurs, and the organization persists in the initial random initialization of the department structure.

Figure 4. Adaptation in loosely coupled structures in stable environments (D = 5, N = 30; 100 runs).



Comparing the four models in figure 4 suggests that first-order adaptation shares strong complementarities with second-order adaptation. In settings with both first-order and second-order adaptation, performance not only increases faster but also asymptotes at a higher level than when there is first-order adaptation alone. But a surprising and, in some sense, reassuring finding is that the process of first-order adaptation continues to be quite useful even when the organization design is misaligned with the corresponding generative structure. This property manifests itself in two ways. First, even in the absence of second-order adaptation, in which, in almost all circumstances, the organizational structures that provide the context for first-order adaptation efforts are misspecified, the process of local adaptation is effective, reaching a performance level of 0.614 by the 100th period.[11] Second, when the generative structure is non-hierarchical, we know from the prior analysis that the process of second-order adaptation results in modest diversity in the set of organizational forms. Despite this, we find no significant performance differences between the hierarchical and non-hierarchical structures. Thus the process of second-order adaptation, even in non-hierarchical structures, is generally effective in arriving at a small subset of functionally equivalent designs in that each of these designs tends to yield equivalent first-order adaptation benefits, lending some support to the principle of equifinality (Gresov and Drazin, 1997). At least in loosely coupled systems, it appears possible to

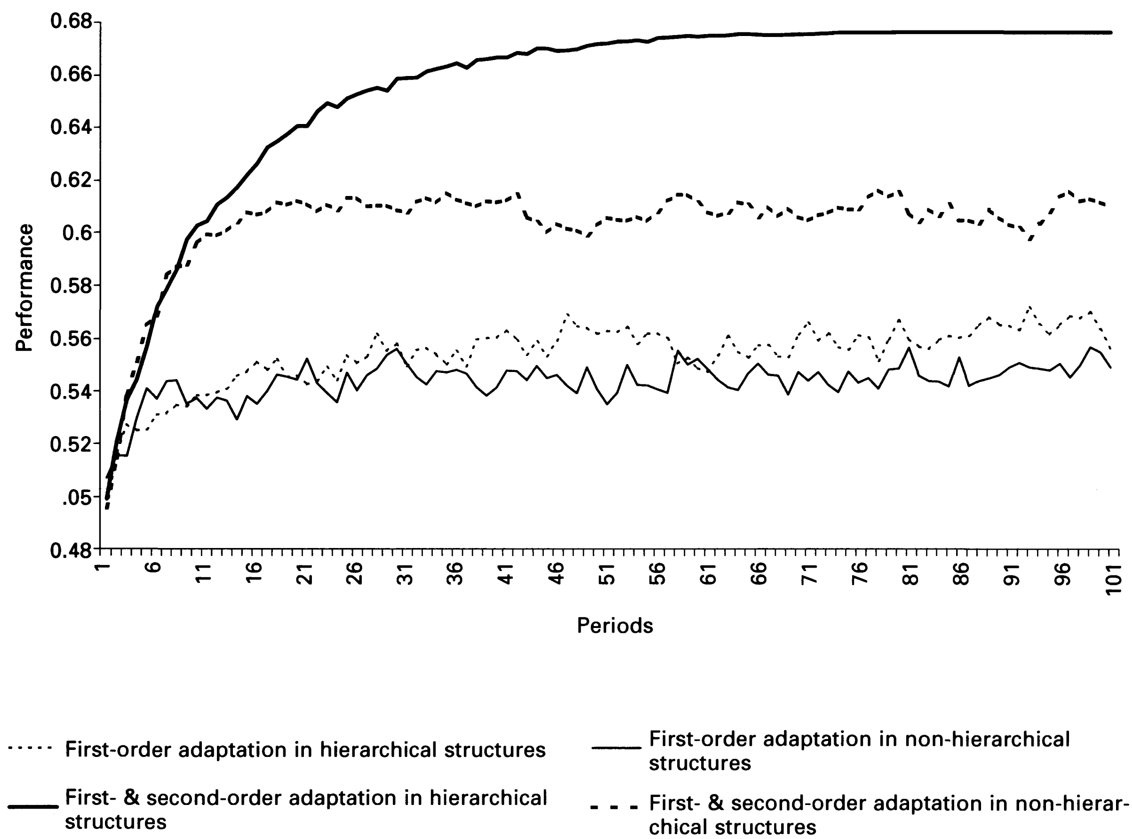
11
In this setting, the performance asymptote is not reached by the 100th period. The process is still moving, though admittedly quite slowly, uphill.

realize the benefits of parallelism and localized adaptation even when the organization design is misaligned with environmental demands. Departures from hierarchy do cause the process of first-order adaptation to be less monotonic, however, particularly in the absence of second-order adaptation.[12] In the absence of hierarchy, actors engage in local adaptation efforts that turn out to be damaging to organizational performance as a whole. This is a consequence of the unanticipated and unknown reciprocal interactions between departments.

Adaptation in tightly coupled settings. We engaged in a parallel analysis in which the generative structure was tightly coupled (figures 1c–1d). Figure 5 indicates the results of first-order adaptation in four tightly coupled structures: hierarchical, with and without second-order adaptation, and non-hierarchical, with and without second-order adaptation. The results here partially diverge from those observed in loosely coupled structures. First, the non-monotonicity in organization performance over time is much greater, because the likelihood of incorrect first-order adaptation efforts is increasing with the degree of coupling between departments. Second, the complementarity between first-order and second-order adaptation is robust even in tightly coupled structures. First-order adaptation in conjunction with second-order adaptation tends to outperform the former alone.

12
The degree of non-monotonicity is somewhat masked by the fact that the reported results are averages over 100 runs. Single runs of the model exhibit a greater degree of non-monotonicity.

Figure 5. Adaptation in tightly coupled structures in stable environments (D = 5, N = 0; 100 runs).



These results lend robustness to the findings of the first set of experiments. If the condition of hierarchy is met, second-order adaptation is quite effective, and first-order adaptation is then useful in generating performance improvements at the department level. Interestingly, the performance asymptote (0.676) here is not statistically significantly different from the performance asymptote (0.684) for loosely coupled structures (see figure 4). This suggests that if the underlying structure is hierarchical and designers engage in second-order adaptation, the success of first-order adaptation efforts is not sensitive to the degree of coupling.

The violation of hierarchy, however, tends to be damaging to first-order adaptation efforts. The disruptive consequences of first-order adaptation when hierarchy is violated are somewhat mitigated by second-order adaptation. Even though we found that the initial diversity of organizational forms persists in the face of second-order adaptation in non-hierarchical and tightly coupled structures, it seems that identifying this subset of designs enhances the effectiveness of first-order adaptation as compared with the random grouping of functions when organizations engage in first-order adaptation alone. Thus even when hierarchy is violated, the process of second-order adaptation is an extremely useful design activity because it results in more orderly structures that facilitate the process of first-order adaptation. This strengthens our initial findings on equifinality in loosely coupled structures.

The results in the stable environment therefore indicate that second-order adaptation shares strong complementarities with first-order adaptation efforts. In the extreme case, when the generative structures are neither hierarchical nor loosely coupled, first-order adaptation efforts without second-order adaptation are largely futile. In general, the violation of hierarchy is less critical to first-order adaptation efforts than the violation of loose coupling.

The impact of environmental change on the complementarity of first- and second-order adaptation. We found that first-order and second-order adaptation share strong complementarities in stable environments. Because environmental change renders second-order adaptation relatively less effective, we sought to examine whether the observed complementarity of first-order and second-order adaptation is robust in the presence of environmental change by replicating the experiment including first-order and second-order adaptation with the addition of environmental change set at $\Delta = 0.05$. As expected, the performance of organizations declined somewhat in a regime of modest environmental change. Otherwise the pattern of results for both loosely coupled structures and tightly coupled structures were largely identical to that in figure 4 and figure 5, respectively, with the complementarities between first-order and second-order adaptation largely robust to modest levels of environmental change.[13]

In the first set of experiments that modeled the process of second-order adaptation alone, as the size of the organization and the probability of environmental change increased, respectively, the marginal value of second-order adaptation declined. The simple intuition here was that when the envi-

13
These results are not included due to space constraints, but they are available from the authors on request.

ronment changes faster than the rate at which organizations can effectively adapt their organization designs, then such adaptations are likely to be futile (Hannan and Freeman, 1984). We examine this possibility here as well.

From an evolutionary standpoint, because selection will tend to favor higher-performing organizations, if second-order adaptation generates performance gains, then organizations that engage in second-order adaptation will have an evolutionary edge over organizations that do not engage in second-order adaptation. Conversely, if increases in organization size and the frequency of environmental change, respectively, obliterate the value of second-order adaptation, then we should find that such efforts at second-order change do not provide any evolutionary edge. In this case, we should find that organizations that are inertial, i.e., do not engage in second-order adaptation, should face no differential selection pressures as compared with organizations that do engage in second-order adaptation. We investigate this possibility by populating the landscape with 100 organizations with a randomly specified number and composition of departments and settings for the decision variables. We set $N = 60$, $D = 5$, and $\Delta = 0.25$. All 100 organizations engage in first-order adaptation, but 50 randomly selected organizations also engage in second-order adaptation every period, while the remaining 50 are inert. In each period, 100 organizations are selected with replacement, and we track the number of surviving organizations that are inert with respect to their structure and the number of survivors that engage in second-order adaptation. An increase in the population of inert firms would suggest that inert firms enjoy an evolutionary advantage, whereas a significant decrease would indicate an evolutionary disadvantage.

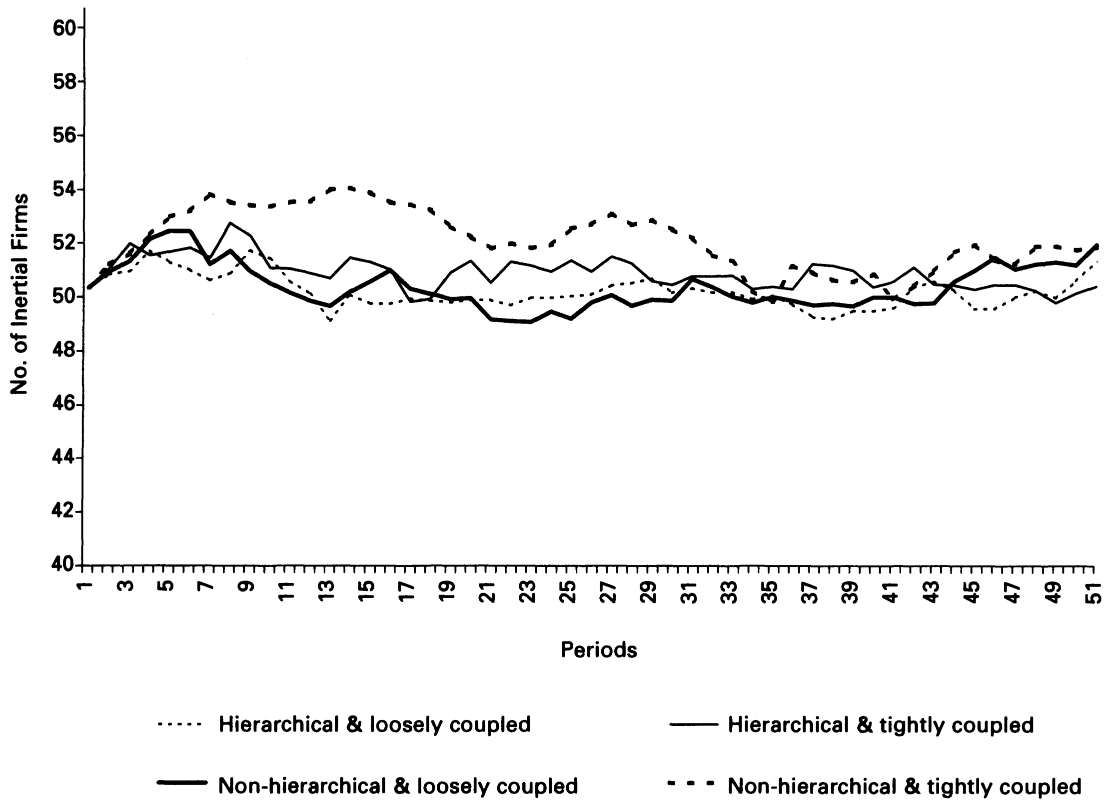
Figure 6 graphs the number of inert organizations that survive in each period of the simulation in each of the four generative structures. The results confirm the relative futility of second-order adaptation.[14] The population of inert firms continues to drift randomly around 50, suggesting that they face no significant advantage or disadvantage compared with firms that engage in second-order adaptation.

At the end of the experiment, there was no statistically significant difference in the average performance levels of the inert and non-inert organizations in all four structures. Examining the variance in performance over the 50 simulation periods, however, we find that populations of organizations that include second-order adaptation exhibit twice the variance in performance as compared with organizational populations that remain inert with respect to their structure. This result confirms the intuition behind Hannan and Freeman's (1984) argument that adaptation of organization forms reduces reliability rather than enhancing performance when the environment changes faster than the pace at which organizations adapt.

The results including environmental change suggest that when change is episodic and infrequent, then the complementary effects of first-order and second-order adaptation are robust. But as organizations grow larger, slowing the effec-

14
We ran these models for only 50 periods rather than 100 because there is no additional information conveyed in modeling the second 50 periods. Also, this analysis took about 200 hours to run on a state-of-the-art PC. Thus, reducing the simulated periods was a pragmatic concern as well.

Figure 6. Adaptation and selection in changing environments (D = 5, N = 60, Δ = 0.25; 100 firms, 100 runs).



tiveness of second-order adaptation, and the rate of environmental change increases, then second-order adaptation becomes largely ineffective. In such settings, the processes of first-order and second-order adaptation cease to be complements. Table 1 summarizes these results, the implications of which we discuss in the following section.

Table 1

Summary of the Results of the Analyses

Generative structure	Second-order adaptation	First-order adaptation	Complementarity of first-order and second-order adaptation
Hierarchical and loosely coupled	Effective	Effective	Strong
Non-hierarchical and loosely coupled	Moderately effective	Effective	Strong
Hierarchical and tightly coupled	Effective	Ineffective	Strong
Non-hierarchical and tightly coupled	Ineffective	Ineffective	Moderately strong

DISCUSSION

The primary objective of this paper was to begin to explore a fundamental set of questions about organization design, including the feasibility and value of design efforts (i.e., second-order adaptation) and the interrelationship between design efforts and incremental adaptation efforts (i.e., first-order adaptation). Simon (1962) argued strongly both that complex systems tend to be hierarchical and loosely coupled and that individual cognition is substantially bounded relative to the complexity of the task environments that people face (Simon, 1955, 1957). Again, for Simon, these two properties, one of systems and the other of individuals, raise the question of to what extent the architecture of complexity (i.e., hierarchy and decomposability) is the ultimate arbiter of feasible and effective boundedly rational design efforts. This constitutes a rather fundamental puzzle for modern organization theory as well, one closely related to the long-standing debate in the literature between contingency perspectives on organizational change that suggest both a high level of plasticity in organizations and, at least implicitly, a high level of cognitive reasoning on the part of managers and ecological perspectives that treat organizations as being relatively inert or subject to dysfunctional consequences as a result of change efforts. Our work sought to engage these important questions in an even-handed manner that recognizes both the constraints on adaptation efforts and the importance of the structure of the firm's task environment.

In general, we found that the underlying structure of complexity is an important determinant of the success of design efforts. In particular, hierarchy was shown to be a necessary and sufficient condition for the success of design efforts, in contrast to the relatively greater saliency given to the property of loose coupling in this literature (Simon and Ando, 1961; Simon, 2002). But the finding shows that loose coupling moderates the violation of hierarchy in terms of facilitating design efforts. This finding on the role of hierarchy and loose coupling is generally robust to both variations in the size of the organization and its complexity (i.e., number of departments and the nature of interactions between them). The principle of hierarchy (i.e., asymmetry in between-department interdependence) facilitates the process by which boundedly rational search for organizational forms helps designers evolve toward and stabilize on appropriate forms. In contrast, in the absence of hierarchy (i.e., between-department interactions are reciprocal), the local search process never ceases searching for the appropriate assignment of decision choices to departments. Reciprocal interdependence triggers a cycling behavior wherein the reciprocally interdependent decisions are continually reassigned from one department to another. The locally rational designers have no way of stopping this incessant searching. Thus the appropriate design of non-hierarchic structures requires actors to have a sophisticated, perhaps implausibly so, global sense of the interdependencies. An empirical implication of this finding is that instances in which one observes an on-going pattern of organizational restructuring (see Eccles and Nohria, 1992) may stem from reciprocal interdependence among activities. In such settings, stability in the organizational form can only result if the organization is willing to accept some degree of apparent misspecification of the organizational structure.

In terms of the chicken-and-egg dilemma that Simon posed, our analysis suggests that the underlying structure of complexity is an important arbiter of the success of human design efforts. Structures that are non-hierarchical and tightly coupled do not easily lend themselves to effective analysis and design efforts, while structures that are hierarchical (or if not hierarchical, loosely coupled) are amenable to boundedly rational design efforts. Even for non-hierarchical and tightly coupled structures, the product of design efforts is still better than random designs. Though this is not observed in the reduction in diversity of organizational forms, the usefulness of design efforts to first-order adaptation is clear from the results of experiment 3. Thus we infer that the usefulness of boundedly rational design efforts is not limited to just hierarchical and loosely coupled structures. It broadly extends to other structures that violate the two properties. Nevertheless, the benefits of design efforts differ both qualitatively and quantitatively across the four different structures. In this regard, our analysis helps formalize and extend Simon's intuitions and provide some boundary conditions around the direction of causality between the architecture of complex systems and bounded rationality.[15]

The second research question examined how environmental change hampers the usefulness of design efforts. We found that the relative efficacy of adaptive efforts in hierarchical structures persists with moderate levels of environmental change, but as the rate of environmental change increases or organizations get larger, the capacity to adapt effectively recedes. Our results thus provide a potential resolution to the ambiguous empirical findings in the literature on the effects of organizational change (see Carroll and Hannan, 2000: 371). When the rate of environmental change is modest, adaptation yields survival benefits. In contrast, when the rate of environmental change is high, adaptation does not yield survival benefits. Similarly, larger organizations are slower to adapt, suggesting that they are likely to be more vulnerable when environmental change is rapid. Perhaps the divergence in empirical findings is a function of examining different rates of environmental change or is due to variations in organization size across studies.

We also examined the conditions under which design efforts (i.e., second-order adaptation) inhibit or facilitate the process of first-order adaptation. The main contingencies we examined were (1) the four states of the world circumscribed by the two dimensions of complexity, i.e., hierarchy and degree of coupling, and (2) the frequency of environmental change. We found that first-order and second-order adaptation were generally complements, though second-order adaptation by itself was completely ineffective in non-hierarchical and tightly coupled structures. The degree of complementarity, though, depends on the nature of the underlying interaction structure. Whereas the complementarity is non-zero and highly positive in loosely coupled structures, it is significantly lower when the underlying structure is non-hierarchical and tightly coupled. The reason we observed the complementarity is that second-order adaptation, even if unsuccessful, is reasonably effective in identifying the neighborhood of high-performing organizational forms. From the standpoint of first-order adaptation, specifying a design that is in the vicinity of the correct design is still significantly better than a random configuration.

An examination of the summary results in table 1 reveals an interesting paradox. On the one hand, design efforts (second-order adaptation) are highly effective in hierarchical structures and less useful in non-hierarchical structures. This finding

15
In examining Simon's chicken-and-egg dilemma, we did not vary the extent of presumed rationality in search processes. Holding the rationality underlying the search processes constant but varying the underlying architecture of complexity, however, allowed us to address whether boundedly rational search processes are largely ineffective in settings that are non-hierarchical and non-decomposable. Thus we were able to address the causality question without varying the rationality underlying the search processes.

encourages design efforts in the former and cautions against it in the latter. On the other hand, first-order adaptation by itself is reasonably effective in loosely coupled structures but completely ineffective in tightly coupled structures in the absence of second-order adaptation. From the standpoint of performance improvement through first-order adaptation, the success of design efforts in loosely coupled structures is relatively less valuable than the imperfect design efforts in non-hierarchical and tightly coupled structures. Thus the results of first-order and second-order adaptation taken together suggest that incremental performance improvement efforts will benefit from organization design efforts even in non-hierarchical and tightly coupled structures in spite of the relative ineffectiveness of design efforts in such settings. The contingent quality of the architecture of complexity is starkly visible in this result.

In a related vein, our results also reaffirm and formalize the intuition behind Simon's architecture of complexity: the dual properties of hierarchy and near-decomposability. Whereas hierarchy is a necessary and sufficient condition for the success of design efforts (second-order adaptation), near-decomposability is a necessary and sufficient condition for the success of incremental performance improvement efforts (first-order adaptation). If first-order and second-order adaptation are both crucial activities of complex organizations, the dual properties of hierarchy and near-decomposability are undeniably central to their architectures, though each plays a distinct role, a distinction that the prior literature had not clearly identified.

Finally, the results of our analysis provide a useful micro-foundation for the burgeoning research on modularity (Baldwin and Clark, 2000; Garud, Kumaraswamy, and Langlois, 2001). Modularity is a design principle that advocates designing structures based on minimizing interdependence between modules and maximizing interdependence within modules. Much of the extant research on modularity has sought to contrast modular architectures with integrated architectures and document the benefits of modular designs. Little research has thus far grappled with the issue of whether and how good modular designs may be achieved in the face of complexity (Ethiraj and Levinthal, 2004). This is an important question, particularly if the benefits of modularity are contingent on achieving good modular designs. If such modular architectures are unrealizable through boundedly rational design efforts, then the benefits of modularity are moot. In this respect, the results reported here are encouraging. We found that relatively local and incremental processes can be used to identify useful, if not optimal modules in structures that have some inherent hierarchy and decomposability.

Collectively, this is an important set of findings that brings to the surface the question of how boundedly rational actors are to design organizations that are intended to economize on the coordination capabilities of these actors. We showed that organization design need not be the product of divine design but may derive from an evolutionary process. At the same time, the work leaves unanswered many other important questions. We have treated the design problem as one of discovering an unknown but latent generative structure. We have not addressed the possible endogeneity of the underlying interaction structure itself. Nevertheless, we view the current work as an important step forward in considering the search for the architecture of complex organizations.

REFERENCES

Adler, P. S., and B. Borys
1996 "Two types of bureaucracy: Enabling and coercive." Administrative Science Quarterly, 41: 61–89.

Adler, P. S., and K. B. Clark
1991 "Behind the learning curve: A sketch of the learning process." Management Science, 37: 251–267.

Adler, P. S., B. Goldoftas, and D. I. Levine
1999 "Flexibility versus efficiency? A case study of model changeovers in the Toyota production system." Organization Science, 10: 43–69.

Aldrich, H.
1979 Organizations and Environments. Englewood Cliffs, NJ: Prentice-Hall.

Amburgey, T. L., D. Kelly, and W. P. Barnett
1993 "Resetting the clock: The dynamics of organizational change and failure." Administrative Science Quarterly, 38: 51–73.

Argote, L., S. L. Beckman, and D. Epple
1990 "The persistence and transfer of learning in industrial settings." Management Science, 36: 140–154.

Argyris, C., and D. A. Schön
1978 Organizational Learning: A Theory of Action Perspective. Reading, MA: Addison-Wesley.

Arrow, K. J.
1974 The Limits of Organization. New York: W. W. Norton.

Astley, W. G., and A. H. Van de Ven
1983 "Central perspectives and debates in organization theory." Administrative Science Quarterly, 28: 245–274.

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

Bartlett, C. A., and S. Ghoshal
1989 Managing Across Borders: The Transnational Solution. New York: McGraw-Hill.

Bartunek, J. M.
1984 "Changing interpretive schemes and organizational restructuring: The example of a religious order." Administrative Science Quarterly, 29: 355–372.

Baum, J. A. C., and J. V. Singh
1994 "Organizational hierarchies and evolutionary processes: Some reflections on a theory of organizational evolution." In J. A. C. Baum and J. V. Singh (eds.), Evolutionary Dynamics of Organizations, 3–20. New York: Oxford University Press.

Carroll, G. R., and M. T. Hannan
2000 The Demography of Corporations and Industries. Princeton, NJ: Princeton University Press.

Chandler, A. D.
1962 Strategy and Structure: Chapters in the History of the American Industrial Enterprise. Cambridge, MA: MIT Press.

Clark, K. B., and T. Fujimoto
1991 Product Development Performance. Boston: Harvard Business School Press.

Cohen, M., and R. Axelrod
1999 Harnessing Complexity: Organizational Implications of a Scientific Frontier. New York: Free Press.

Cooper, R., and R. S. Kaplan
1992 "Activity-based systems: Measuring the costs of resource usage." Accounting Horizons, 6: 1–13.

Cummings, S.
1995 "Centralization and decentralization: The never-ending story of separation and betrayal." Scandinavian Journal of Management, 11: 103–117.

Cusumano, M. A., and R. W. Selby
1998 Microsoft Secrets: How the World's Most Powerful Software Company Creates Technology, Shapes Markets, and Manages People. New York: Simon & Schuster.

DiMasi, J. A.
2001 "Risks in new drug development: Approval success rates for investigational drugs." Clinical Pharmacology and Therapeutics, 69: 297–307.

Dove, A.
2001 "Betting on biogenerics." Nature Biotechnology, 19: 117–120.

Dranove, D., and D. Meltzer
1994 "Do important drugs reach the market sooner." RAND Journal of Economics, 25: 402–423.

Eccles, R. G., and N. Nohria
1992 Beyond the Hype: Rediscovering the Essence of Management. Boston: Harvard Business School Press.

Eisenhardt, K. M., and S. L. Brown
1999 "Patching: Restitching business portfolios in dynamic markets." Harvard Business Review, 77(3): 72–82.

Ethiraj, S. K., and D. A. Levinthal
2004 "Modularity and innovation in complex systems." Management Science, 50: 159–173.

Fiol, M. C., and M. A. Lyles
1985 "Organizational learning." Academy of Management Review, 10: 803–813.

Garey, M. R., and D. S. Johnson
1990 Computers and Intractability: A Guide to the Theory of NP-Completeness. San Francisco: W.H. Freeman.

Garud, R., A. Kumaraswamy, and R. Langlois
2001 Managing in the Modular Age: Architectures, Networks and Organizations. London: Blackwell.

Goldberg, D. E.
1989 Genetic Algorithms in Search, Optimization and Machine Learning. Reading, MA: Addison-Wesley Longman.

Gresov, C., and R. Drazin
1997 "Equifinality: Functional equivalence in organization design." Academy of Management Review, 22: 403–428.

Hannan, M. T., and J. Freeman
1977 "The population ecology of organizations." American Journal of Sociology, 82: 929–964.
1984 "Structural inertia and organizational change." American Sociological Review, 49: 149–164.

Henderson, R. M., and K. B. Clark
1990 "Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms." Administrative Science Quarterly, 35: 9–30.

Kauffman, S. A.
1993 The Origins of Order: Self-organization and Selection in Evolution. New York: Oxford University Press.

Kelly, D., and T. L. Amburgey
1991 "Organizational inertia and momentum: A dynamic model of strategic change." Academy of Management Review, 34: 591–612.

Lant, T. K., and S. J. Mezias
1990 "Managing discontinuous change: A simulation study of organizational learning and entrepreneurship." Strategic Management Journal, 11: 147–179.
1992 "An organizational learning model of convergence and reorientation." Organization Science, 3: 47–72.

Lawrence, P. R., and J. W. Lorsch
1967 Organization and Environment: Managing Differentiation and Integration. Homewood, IL: Richard D. Irwin.

Levinthal, D. A.
1997 "Adaptation on rugged landscapes." Management Science, 43: 934–950.

Macduffie, J. P.
1995 "Human resource bundles and manufacturing performance: Organizational logic and flexible production systems in the world auto industry." Industrial and Labor Relations Review, 48: 197–221.
1997 "The road to 'root cause': Shop floor problem-solving at three auto assembly plants." Management Science, 43: 479–502.

Marengo, L., G. Dosi, P. Legrenzi, and C. Pasquali
2000 "The structure of problem-solving knowledge and the structure of organizations." Industrial and Corporate Change, 9: 757–788.

Miller, G. A.
1956 "The magical number seven, plus or minus two: Some limits on our capacity for information processing." Psychological Review, 63: 81–97.

Miner, A. S., and S. J. Mezias
1996 "Ugly duckling no more: Pasts and futures of organizational learning research." Organization Science, 7: 88–99.

Mintzberg, H.
1979 The Structuring of Organizations. Englewood Cliffs, NJ: Prentice-Hall.

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

Nickerson, J., and T. Zenger
2002 "Being efficiently fickle: A dynamic theory of organizational choice." Organization Science, 13: 547–566.

Perrow, C.
1972 Complex Organizations: A Critical Essay. Glenview, IL: Scott, Foresman.
1999 Normal Accidents. Princeton, NJ: Princeton University Press.

Rivkin, J., and N. Siggelkow
2003 "Balancing search and stability: Interdependencies among elements of organizational design." Management Science, 49: 290–321.

Sanchez, R., and J. T. Mahoney
1996 "Modularity, flexibility, and knowledge management in product and organization design." Strategic Management Journal, 17: 63–76.

Schaefer, S.
1999 "Product design partitions with complementary components." Journal of Economic Behavior and Organization, 38: 311–330.

Scott, W. R.
1998 Organizations: Rational, Natural, and Open Systems, 4th ed. Englewood Cliffs, NJ: Prentice-Hall.

Simon, H. A.
1955 "A behavioral model of rational choice." Quarterly Journal of Economics, 69: 99–118.
1957 Administrative Behavior: A Study of Decision-making Processes in Administrative Organization, 2d ed. New York: Macmillan.
1962 "The architecture of complexity." Proceedings of the American Philosophical Society, 106: 467–482.
2002 "Near decomposability and the speed of evolution." Industrial and Corporate Change, 11: 587–599.

Simon, H. A., and A. Ando
1961 "Aggregation of variables in dynamic systems." Econometrica, 29: 111–138.

Stinchcombe, A. L.
1965 "Organizations and social structure." In J. G. March (ed.), Handbook of Organizations, 153–193. Chicago: Rand-McNally.

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

Tushman, M. L., and P. Anderson
1986 "Technological discontinuities and organizational environments." Administrative Science Quarterly, 31: 439–465.

Tushman, M. L., and E. Romanelli
1985 "Organizational evolution: A metamorphosis model of convergence and reorientation." In L. L. Cummings and B. M. Staw (eds.), Research in Organizational Behavior, 7: 171–222. Greenwich, CT: JAI Press.

Ulrich, K. T., and S. D. Eppinger
1999 Product Design and Development, 2d ed. New York: McGraw-Hill.

Weick, K. E.
1976 "Educational organizations as loosely coupled systems." Administrative Science Quarterly, 21: 1–19.

Williamson, O. E.
1975 Markets and Hierarchies: Analysis and Antitrust Implications. New York: Macmillan.

Wilson, E., and W. Bossert
1971 A Primer of Population Biology. Sunderland, MA: Sinauer Associates Inc.

APPENDIX

Modeling the Generative Structures

Organizations are represented as making a set of N choices or decision variables $[a_1, a_2, a_3, \ldots a_n]$. In figure 1a, the contribution of an individual decision variable, a_i, depends on other decision variables. Thus, decision variable a_1 depends on decision variables a_2, a_3, and a_4. In contrast, decision variable b_3 depends on four other decision variables (a_2, b_2, b_3, b_4). As a result, decision variable a_1 can result in 16 possible levels of performance, depending on its own value (a 0 or 1) and the value of the three other decision variables on which it depends, while decision variable b_3 can take on 32 possible levels of performance, depending on its own value and the value of the four other decision variables on which it depends.

The performance contribution (ω_i) of each decision choice (a_i) is determined both by the state (0 or 1) of the ith decision choice and the states of the j other decision choices on which it depends. Thus,

$$\omega_i = \omega_i(a_i; a_i^1, a_i^2 \ldots a_i^j)$$

The value of ω_i is treated as an i.i.d. random variable drawn from the uniform distribution U [0,1] for each configuration of a_i and the j other decision choices on which it depends. Organization performance Ω is a simple average of the ω_i over the N decision choices.

$$\Omega = \frac{1}{N}\left[\sum_{i=1}^{N} \omega_i\ (a_i; a^1{}_i, a_i^2, \ldots a_i^j)\right]$$

The results are robust to alternative distributional assumptions as well. We ran the analysis with exponential and log-normal distributions and obtained results that are qualitatively similar to those reported here. These results are available from the authors.

We also specified the number of departments and their composition (i.e., the decision variables that would be assigned to a department). For an organization with N decision variables, we created D departments, where the kth department, D_k comprised (N/D) decision variables assigned at random. For a given value of N, we varied the value of D for robustness. We specified the interdependence between departments randomly. For instance, in experiments in which figure 1a characterized the organizational form, we randomly chose two decision variables from each department D_i that affect two randomly chosen decision variables in department D_j (for all $i < j$). Similarly, in figure 1b, we randomly chose one policy each from departments D_i and D_j that affect each other. More generally, overall interdependence in figures 1a and 1b (the loosely coupled structures) was always equal and determined by the formula D[(N/D) * ((N/D) –1)] + 2(D-1), where the first term captures the total interdependence within departments and the second term captures the level of interdependence between departments. Similar procedures were employed in specifying the between-department interactions in figures 1c and 1d. Formally, the total interdependence in figures 1c and 1d was always equal and represented as D[(N/D) * ((N/D) – 1)] + 2*[(N/D) * (N/D)]. The first term captures interdependence within departments and the second term the interdependence between departments.

Second-order Adaptation

The inferential process for second-order adaptation can be formalized as follows. Consider a set of decision variables that are perceived to belong to a department, $(a_i, a_{\neg i}) \in D_\gamma$, where a_i represents a focal decision choice and $a_{\neg i}$ are the remaining set of decision choices within the department D_γ and the organization is defined by a set of departments, $D = \{D_\alpha, D_\beta, D_\gamma, \ldots D_K\}$. The performance of the department is given by

$$\frac{1}{n_{D\gamma}}\sum_{n_{D\gamma}}\omega_i(a_i; a_{\neg i}),$$

where $n_{D\gamma}$ is the number of decision choices in department D_γ . Now, consider a single decision variable, $a_j \in D_\gamma$, that is flipped to a_j' and the resulting performance of each decision choice in the department is observed. Then let A be defined as a set of all decision choices such that

$$A = \left\{a_i : \omega_i(a_i; a_{\neg i \neg j}, a_j) \neq \omega_i(a_i; a_{\neg i \neg j}, a_j') \text{ for all } i \in D_\gamma\right\}$$

The set A identifies the set of all decision choices in D_γ whose performance changes as a result of flipping decision choice a_j. The designers then adopt a simple rule that all decision choices that were unaffected by the search do not belong to the focal department. All such decision choices are then either transferred to a randomly chosen different department or split into a separate department if they constitute a large enough set. The unchanged decision choices in D_γ are transferred into a randomly chosen other existing department if they constitute less than half the total number of decisions in D_γ; otherwise, the unaffected decisions are split into a new department D_{K+1}. If A is an empty set, it means that the performances of all remaining decision choices in D_γ, $(a_{\neg j})$, were unchanged by the flip in a_j suggesting that a_j does not belong to the department. Thus, a_j is transferred to a randomly chosen department D_K. More formally, if

$$A = \{\}, \text{ then } a_j \in D_K, \text{ otherwise,}$$

$$\text{If } nA \leq \frac{nD_\gamma}{2} \left\{ \begin{array}{l} (\neg A \cap a_{\neg j}) \in D_{K+1} \text{ otherwise,} \\ (\neg A \cap a_{\neg j}) \in D_K \end{array} \right\}$$

where, nA and nD_γ represent the number of decision choices in A and D_γ, respectively.

In each period, we also consider combining each department with another randomly chosen department. The departments combine if changes in each department affect the other and remain separate otherwise. For instance, consider two teams representing two departments, D_α with decision choices $[a_1, a_2, a_3, \ldots a_i]$, and D_β with decision choices $[b_1, b_2, b_3, \ldots b_j]$. A randomly chosen decision choice from each department, a_i and b_j, respectively, are flipped. The departments D_α and D_β combine to create a new department, D_γ if the performance of department D_β is affected by the flipping of a_i and the performance of department D_α is affected by the flipping of b_j. More formally, if

$$\frac{1}{n_{D\alpha}} \sum_{n_{D\alpha}} \omega_i\,(a_i; a_{\neg i}, b_j') \neq \frac{1}{n_{D\alpha}} \sum_{n_{D\alpha}} \omega_i(a_i; a_{\neg i}, b_j) \wedge$$

$$\frac{1}{n_{D\beta}} \sum_{n_{D\beta}} \omega_j(b_j; b_{\neg j}, a_i') \neq \frac{1}{n_{D\beta}} \sum_{n_{D\beta}} \omega_j\,(b_j; b_{\neg j}, a_i)$$

Then, $D_\gamma = D_\alpha \cup D_\beta$

First-order Adaptation

Formally, consider a decision choice $a_j \in D_K$ is flipped to a_j'. Then, if

$$\frac{1}{n_{DK}} \sum_{n_{DK}} \omega_i\,(a_i; a_{\neg(i,j)}\,, a_j') > \frac{1}{n_{DK}} \sum_{n_{DK}} \omega_i\,(a_i; a_{\neg(i,j)}\,, a_j)$$

$$\text{then} \left\{ \begin{array}{l} D_k = (a_{\neg j}\,, a_j') \text{ otherwise} \\ D_k = (a_{\neg j}\,, a_j) \end{array} \right.$$

Modeling Environmental Change

For an organization with N decision variables, we retained the D departments that we specified at the start of the simulation, and following every environmental change, we again randomly reassigned the (N/D) decision variables to each of the departments. We also respecified the interdependence between departments randomly. For instance, in experiments in which figure 1a was the generative structure, in the period when environmental change occurred, we again randomly chose two decision variables from each department D_i that affects two randomly chosen decision variables in department D_j (for all $i < j$). Thus, following each environmental change, we respecified the coupling of decision variables within departments and the nature of between-department interactions that make up the generative structure.

Modeling Selection

We used the standard roulette wheel algorithm (Goldberg, 1989) for modeling selection. More formally,

$$p(s_i) = \frac{\Omega_i}{\sum_{i=1}^{S} \Omega_i}$$

where, $p(s_i)$, the probability of selecting the ith organization is given by the ratio of the performance, Ω_i, of the ith organization to the total performance of all S organizations in the population. The cumulative probability, $P(s_i)$, is then computed as,

$$P(s_i) = \sum_{j=1}^{i} p(s_j)$$

A total of S random numbers r_s distributed i.i.d. in the interval [0, 1] are drawn, and the organizations whose cumulative probability spans a random draw are selected according to the rule, $P(s_{i-1}) \leq r_s \leq P(s_i)$.