Organization Design: The Epistemic Interdependence Perspective

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ORGANIZATION DESIGN:
THE EPISTEMIC INTERDEPENDENCE PERSPECTIVE[1]

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ABSTRACT

We develop a novel analytical framework to study *epistemic interdependence* between agents and the resulting need for *predictive knowledge* as a basis for understanding information processing requirements in organizations, and the implications for organization design. These two new constructs help to sharply distinguish interdependence between tasks and between agents, and highlight why even interdependence between agents need not imply any need for information processing between them. They also help to refine key ideas about organization design.

An extensive literature treats the design of organizations as a means to meet the information processing requirements generated by individuals and groupings of individuals undertaking interdependent activities (e.g. Burton & Obel, 1984; Galbraith, 1973, 1977; March & Simon, 1958; Simon, 1945; Thompson, 1967; Tushman & Nadler, 1978; Van de Ven, Delbeq, & Koenig, 1976). Rooted in the notion of bounded rationality (Simon, 1945), this perspective frames organizations as systems of coordinated activity, and focuses on the costly information processing required to coordinate activities under uncertainty (Galbraith, 1973). This entails "communication and decision making" (Thompson, 1967: 57) as well as the "gathering, interpreting and synthesis of information in the context of organizational decision making" (Tushman & Nadler, 1978: 614). The information processing perspective has also spawned influential offshoots, though it is conceptually distinct from them. These derivatives include structural contingency theory which focuses on particular contingencies such as age, size, technology and the environment (e.g. Donaldson, 2001), as well as configurational theories (e.g. Mintzberg, 1979) that posit ideal types of organizations appropriate for certain combinations of contingencies (Doty, Glick, & Huber, 1993).

Despite the intuitive appeal of its core ideas, empirical validation of the information processing perspective and its offshoots has been challenging (Capon, Farley & Hoenig, 1990; Drazin & Van de Ven, 1985; also see a comprehensive literature review by Dalton et al., 1980), with some suggesting that the evidence has been at best "confusing and contradictory" (Barley, 1986: 78). Several explanations have been offered for this: these include the possibility of equi-final performance for different organizational arrangements (Gresov & Drazin, 1997), institutional and inertial limits on the alignment between organizational structure and context (Hannan & Freeman, 1977; Meyer & Scott, 1983) and the challenge of measuring intervening variables that may obscure the links between high level structural choices and performance (Siggelkow & Rivkin, 2009). Interestingly, the absence of strong empirical validation has not prevented the information processing perspective from remaining central in the pedagogy and practice of organization design (Dunbar & Starbuck, 2006), indicating perhaps the paucity of viable alternatives to guide managerial action.

In this paper, we develop the view that with some important refinements to the information processing perspective, it is possible to comprehend the mixed empirical record to date and to formulate a viable empirical research agenda going forward. Specifically, the theoretical arguments in this paper build on one central insight: *interdependence between tasks need not imply interdependence between the agents performing these tasks*; *and interdependence between agents in turn does not imply a need for information processing between them.* This two-step analytic separation of the interdependence between tasks and the need for information processing between agents is theoretically fruitful, because it helps explain *why*

- interdependence between agents can be modified by an organization designer, even when interdependence between tasks cannot be,
- the structure of tasks and the structure of organizations may not resemble each other,
- organizations facing identical sets of tasks may have different, equally effective organizational structures

While each of these problems in organizational analysis has been noted individually by prior authors (Colfer & Baldwin, 2010; Gresov & Drazin, 1997; Levinthal & Warglien, 1999), we uniquely offer a single common explanation for why these arise. Thus, by sharpening the theory on the central link between interdependence and information processing, we claim significant potential gains in conceptual clarity leading ultimately to better empirical tests.

To clarify the relationships between task interdependence and the need for information processing, we analyze differences in the underlying coordination problems for a given allocation of tasks to individual agents (Schelling, 1960). We argue that the breadth of incentives used to measure and reward the agents, and the scheduling of actions by the agents can generate *epistemic interdependence* – a situation in which one agent's optimal choices depend upon a prediction of another agent's actions. We show that task interdependence is neither necessary nor sufficient for epistemic interdependence to exist between the agents performing the tasks, and that interdependence between agents is necessary but not sufficient for epistemic interdependence to exist between them.

We go on to argue that it is epistemic interdependence, rather than interdependence between agents or tasks per se that makes information processing potentially necessary for coordinated action. Given epistemic interdependence, to coordinate successfully requires creating the necessary *predictive knowledge* through information processing between agents, where predictive knowledge refers to knowledge that enables one agent to act as if he can accurately predict another agent's actions. We argue that organization designers -those explicitly tasked with the goal of improving the performance of the organization- can not only choose organizational structures to aid the generation of predictive knowledge through information processing, but can also influence the extent to which there is epistemic interdependence between agents. The designers' *architectural knowledge* -their understanding of how the components of a system are related to each other (Baldwin & Clark, 2000; Henderson & Clark, 1990; von Hippel, 1990)- allows them to reduce epistemic interdependence among the agents to the extent that their knowledge is relevant and accurate (Colfer & Baldwin, 2010).

In essence, we argue that organization design may be seen as the interplay between the designer's knowledge of how to divide, allocate and measure tasks (architectural knowledge) and the agents' knowledge of how to coordinate their efforts (predictive knowledge). To maintain a given level of organizational performance, the two kinds of knowledge can act as substitutes. Organization design variations can be ascribed to the different levels and rates of formation of architectural and predictive knowledge.[1]

The rest of this paper is organized as follows: The next section distinguishes inter-task and inter-agent interdependence, and shows how a number of highly influential conceptualizations of interdependence in the organization design literature either do not maintain this distinction, or assume that the two are perfectly isomorphic. Since agents, not tasks, process information, this can be problematic. In the subsequent section we define and characterize a third type of interdependence, namely epistemic interdependence, and discuss how it clarifies the conditions under which information processing between agents is necessary. Having established the need for the epistemic interdependence construct and defined it, we use it to revisit the basic theoretical links between interdependence, information processing and the design of organizations. We then present applications of our approach to a small selection of traditional organization design topics, and highlight our key contributions as well as the limitations of our approach before the concluding remarks.

PRIOR CONCEPTUALIZATIONS OF THE LINKS BETWEEN INTERDEPENDENCE & INFORMATION PROCESSING

We take as uncontroversial the central premise in the prior literature that modes of organizing differ in their capacities to process information, as this defines the information processing perspective on organization design (e.g. Galbraith, 1977; March & Simon, 1958; Simon, 1945; Thompson, 1967; Tushman & Nadler, 1978). Rather, our suggested refinements focus on the links between interdependence and information processing. This link is treated explicitly in a number of papers on the theory of organization design, but in our view a key limitation is that interdependence between tasks is typically treated as synonymous with (or as fully determining) the need for information processing between agents performing the tasks.

We take a "task" as our fundamental unit of analysis. It may be thought of as a production technology - it is a transformation of inputs into outputs in a finite time period. For the purpose of this analysis, it can also be thought of as an action or a choice to be made by an agent. Since tasks have inputs and outputs, they have an associated value (determined by the difference between the benefits of the outputs and the cost of the inputs- as seen by the designer of the system). Whether the task is a design task or a production task will not influence the rest of our discussion (see also Ethiraj & Levinthal, 2004a, b), though we are mindful that there are qualitative empirical differences between them (Baldwin & Clark, 2000).

The term "interdependence" in the organization design literature encompasses both asymmetric (one-sided) and symmetric (two-sided) dependence (e.g. sequential interdependence). We follow conventional usage, and use interdependence for both, but specify whether we refer to symmetric or asymmetric interdependence when the difference matters.

Task Interdependence

We say that two tasks are *interdependent when the value generated from performing each is different when the other task is performed versus when it is not*. The tasks are independent if the value to performing each is the same whether the other task is performed or not. As a consequence the combined value created when independent tasks are performed is the same as the sum of the values created by performing each task alone (e.g. pooled interdependence in Thompson, 1967, where each task makes a discrete contribution to the whole).

This definition encompasses a range of prior conceptualizations of task interdependence. For instance, tasks can be jointly dependent on the same limited inputs (e.g. Burton & Obel, 1984; Malone & Crowston, 1994). In this case, performing each task alone will result in different levels of consumption of the input (and therefore output and value) than performing both tasks (economies of scope display this property). Tasks can also be interdependent with respect to their outputs - which may be complements or substitutes (Milgrom & Roberts, 1995). By definition, the existence of complementarity or substitution relationships between the outputs implies that performing each task alone will result in different values for each than when performing both tasks. Such complementarity/substitution relationships are explicitly modeled in super- (or sub-) modular production functions (e.g. Milgrom & Roberts, 1990). They are implicit as epistatic interactions in fitness landscapes (e.g. Levinthal, 1997) and dependencies between (design) tasks in (Design) Task Structure Matrices (Baldwin & Clark, 2000; Eppinger, 1991; Steward, 1981).

Finally, task 1's output may form the input to task 2 (e.g. sequential and reciprocal interdependence in Thompson, 1967). In this case, task 2 will be asymmetrically interdependent with task 1, but the converse need not be true (it will depend on whether the value of task 1 changes with the performance of task 2 or not). Thus, different kinds of interdependencies between tasks can be represented analytically in terms of the different ways that each task's inputs and outputs enter a combined value function, but *the defining feature of interdependence between two tasks is that the value of performing one task is different when the other task is performed.*

Agent Interdependence

In contrast to task interdependence, interdependence between agents has the following general form: given an allocation of tasks to agents A and B, there is asymmetric interdependence of A on B if the reward to A from A's actions depends on the actions taken by B but B's reward does not depend on A's actions. *Symmetric interdependence exists when the reward to A from A's actions depends on B's actions and vice versa.* This conceptualization appears explicitly in the analysis of reward interdependence (Kelley & Thibaut, 1978), power (Emerson, 1962; Pfeffer & Salancik, 1978) and in game theory in general (e.g. von Neuman & Morgenstern, 1944).

Notwithstanding this conceptual distinction between inter-task and inter-agent interdependence, the two are typically treated synonymously in the information processing literature on organization design (McCann & Ferry, 1979; Mohr, 1971; Thompson, 1967; Van de Ven et al., 1976). Other approaches, which model task interdependencies as constraints in linear programs (e.g. Burton & Obel, 1984) or through Design Structure Matrices (e.g. Baldwin & Clark, 2000) distinguish conceptually between task and agent interdependencies, but assume these are isomorphic. As we will show, this assumption is valid only for a fairly specific set of circumstances.

Decoupling Task from Agent Interdependence

Before we analyze when interdependence results in greater information processing needs, let us consider the relationship between agent and task interdependence more closely. Since ultimately it is agents, not tasks, who process information, it is useful to ask whether interdependence between tasks implies interdependence between the agents performing the tasks. Two examples suffice to show that interdependence between tasks is neither necessary nor sufficient for interdependence between agents to exist. Consider an allocation of tasks 1 and 2 to agents A and B:

First, let us consider the case when the tasks are *independent*- the value of each task is the same, whether the other is also performed or not. Drawing on an example with an illustrious heritage, imagine A and B must each make 100 pins (i.e. no specialization) in a pin factory (Smith, 1776). The value of 200 pins to the factory owner (presumed to be the designer of this system) is no different from the sum of the value of 100 + 100 pins. Assume however that each agent is paid their daily wage only if both tasks are performed- i.e. if the owner sees 200 pins produced by the end of the day. Then, for each agent, the reward for their efforts to meet their individual target of 100 pins depends on the other's efforts, because A may still get no wages despite producing 100 pins if B fails to do so, and vice versa. In this situation, by definition, there is interdependence between the agents. They will need to observe each other's progress and communicate -process information- in order to minimize the dangers of putting in efforts but failing to receive any rewards, even though each agent's production of pins (the task) is independent of the other's. Thus task interdependence is not necessary for interdependence between agents to exist. Reward interdependence is sufficient.

Next consider the case where the tasks are *interdependent*. With specialization in the pin factory, A now makes 300 pin heads and B makes 300 pin tails, which can be soldered together to produce 300 pins by the end of the day. The tasks are interdependent, because 300 pin heads alone or 300 pin tails alone are worthless, whereas 300 pins are worth something to the factory owner. Assume however that the factory owner agrees to pay each worker their daily wage as long as he is satisfied that each has produced 300 heads and 300 tails, respectively. Then for each agent the reward to their efforts to meet their individual target of 300 heads or tails does not depend on the other's efforts, because A will still get her wages as long as she produces 300 heads, even if B fails to produce a single tail. In this situation, by definition, there is no interdependence between the agents. They have no need to observe each other's progress or communicate and can in fact work in ignorance of the very existence of the other. Therefore task interdependence is not sufficient for interdependence between agents to exist.

For an example of the decoupling between task and agent interdependence in a less stylized setting, consider the cell phone industry. For the case of *independent* tasks and *interdependent* units, assume that unit A is the division responsible for developing a cell phone's hardware components and unit B develops the operating system (OS). While the two unit managers could be rewarded primarily on the firm's overall sales, their individual non-specialized products can be sold on separate external markets. For example, the hardware unit could sell the phones using a competitor's operating system (e.g. Nokia selling its smart phones with Microsoft's Windows Phone 7 OS) and the software unit could offer their product to other cell-phone manufacturers (e.g. Nokia's Symbian OS runs on some Sony Ericsson phones). While the handsets and the operating system will be compatible (Nokia's basic models run the Symbian OS), the tasks of producing each are independent to the extent that the sum of the products' value in the external market is identical to the value generated from selling them as a bundle (this assumption is reasonable as historically, Symbian was developed through a partnership between different cell phone manufacturers and is thus not a native Nokia product).

On the other hand, Apple Inc. and Research in Motion (RIM) are examples of cell phone manufacturers whose hardware and software units face *interdependent* tasks - the iPhone is only sold with iOS (Apple's cell phone OS) and all BlackBerries run BlackBerry OS (RIM's OS), and in neither case are the handsets or the OS sold separately in the external market. While this conforms to the definition of interdependent tasks (their joint value is different from the sum of the separate output values because of co-specialization), the unit-heads of the two units creating these products could in theory be independent, if they are rewarded primarily on some measure of their own unit's performance that does not depend on the other units behaviour (Argyres, 1995); for instance on design quality of handsets for the hardware unit, and total number of 'bugs' (or rather lack thereof) for the software unit. (If such measures cannot be found, then de facto they are interdependent).

Thus, task interdependence is neither necessary nor sufficient to produce interdependence between the agents performing the tasks. Rather, interdependence between agents depends entirely on a key feature of their reward structure- *incentive breadth.* This refers to the level of aggregation at which an agent's actions (or their results) are measured and rewarded. In the case of two agents, narrow incentives correspond to the reward of individual actions or their results in a manner that makes them independent of the other agent's actions. For instance in the specialized pin factory example, when each worker is paid as long she produces her 300 heads or 300 tails respectively, they face a narrow incentive structure. Broad incentives correspond to the reward of individual actions or their results in a manner that makes them at least partly dependent on the other agent's actions. If one of the workers in the example above was paid only on delivering 300 complete pins made by assembling the heads she makes with the tails the other worker makes, she is in effect facing broad incentives. If both are paid their wages only on delivery of 300 complete pins, both face broad incentives (Kretschmer & Puranam, 2008).

Agents are interdependent when they face broad incentives, but are independent when they face narrow incentives. Put differently, interdependence between tasks is assessed by examining the value function representing the combined system of tasks, while interdependence between agents depends on the reward function of the agents. Since in general these will not be identical, there will be a corresponding divergence between task and agent interdependence.[2]

Once we acknowledge that interdependence between tasks and agents are orthogonal constructs, the efforts in the classical literature to link task interdependence to the need for information processing between agents (e.g. Thompson, 1967) appear puzzling, unless a broad incentive structure was implicitly assumed. However, even this assumption cannot have been universal: Consider the case of pooled task interdependence, which involves a situation where each action makes an independent contribution to the whole (Thompson, 1967). Yet, the agents performing these tasks will be interdependent if they face broad incentives. To make pooled interdependence correspond to a situation where minimal or no information processing were required between the agents, we would need to assume a narrow incentive structure.

From Agent Interdependence to Information Processing

Even with appropriate assumptions about the incentive structure, knowing the nature of task and agent interdependence is still insufficient to precisely specify whether information processing will be necessary between agents. For instance, the most significant stream of work in information processing and organization design has relied on the directionality of workflows between tasks to understand implications for information processing among agents (McCann & Ferry, 1979; Thompson, 1967; Van de Ven et al., 1976). It is easy to show that the direction of information flow between agents needed to coordinate activities does not necessarily correspond to the direction of workflow. For example, if A and B were a biotechnology and pharmaceutical company forming a Joint Venture, where A specialized in research while B specialized in development and distribution and they formed a profit sharing agreement, A would require information from B to produce a drug that fits into B's product portfolio. On the other hand, B could wait for the finished product before she starts her development and distribution efforts. Thus while A and B are interdependent, A needs to process information about B but not vice versa, even though B's task is dependent on A's for inputs, and both agents are interdependent with each other because of the incentive structure.

This asymmetric pattern of information processing requirements does not arise from the pattern of task interdependence per se but rather depends on the *sequence* of actions. Assume that A and B are two teams of consultants in a consulting company that are working for the same client; team A is tasked to design a more effective organizational structure while team B is asked to rebrand the logo for the client. While the tasks are independent, each team may only be paid the annual bonus if *both* teams deliver projects that satisfy the client. Assume team A finishes first. Given the reward dependence between the teams, team A will not want to expend a lot of (fruitless) effort if team B ends up doing a sub-standard job - thus, team A needs to choose its effort level based on its expectation –which may be formed through communication and information processing- of whether team B will put in more or less effort.

These examples illustrate that in a dyad of interdependent agents, whether *information processing* is necessary and by whom depends on *scheduling* -the sequence of actions; interdependence between agents is not sufficient to create a need for information processing between them. To be precise, what matters for information processing is whether the agents act before or after *knowing* the other's actions, not on chronological time per se. In the consulting company example above, if the client's reactions are not widely known, team B may still need to engage in information processing to learn how team A did in order to assess if they should put in a lot of effort themselves, even if team A's project is complete.

It is of course well known that the timing of actions has critical implications for how easy or difficult it is for agents to coordinate their actions (Schelling, 1960). Van de Ven et al. recognized this when they added team interdependence, which exists when "there is no measurable temporal lapse in the flow of work between unit members" (1976: 325) to the top of Thompson's Guttman scale featuring pooled, sequential and reciprocal interdependence. However, by combining these onto a common scale, they effectively treated inter-agent and inter-task interdependencies as equivalent.

In sum, we have shown that i) task interdependence is neither necessary nor sufficient for interdependence between the agents performing the tasks, and ii) interdependence between agents is necessary but not sufficient to create a need for information processing between them. Neither conception of interdependence, individually or jointly, is sufficient to understand information processing requirements for a given allocation of tasks among agents. In the following section we argue that information processing will be primarily necessary in the presence of coordination problems between agents, for which the scheduling of tasks plays a critical role. Given that neither conception of interdependence discussed above results in such coordination problems per se, we identify and define a third kind of interdependence that gives rise to coordination problems and requires information processing activities to be solved.

EPISTEMIC INTERDEPENDENCE & INFORMATION PROCESSING

The classical literature on organization design has emphasized that information processing activities help to coordinate the activities of agents in organizations (e.g. Galbraith, 1977; March & Simon, 1958; Simon, 1945; Thompson, 1967; Tushman & Nadler, 1978). Coordination problems have of course been extensively studied across a range of social sciences, and not only in the field of organization design. Coordination failures occur when interacting individuals are unable to anticipate each other's actions and adjust their own accordingly. Coordination failures are manifested as delay, misunderstanding, poor synchronization and ineffective communication. These ideas are well entrenched in game theory (Schelling, 1960), linguistics (Clark, 1996), social psychology (Heath & Staudenmayer, 2000) and organization theory (March & Simon, 1958; Weick, 1993). In contrast, cooperation failures occur when interdependent individuals are not motivated to achieve the optimal collective outcome because of conflicting incentives. Coordination failures can occur quite independently of cooperation failures – even when incentives are fully aligned (Camerer, 2003; Grant, 1996; Heath & Staudenmayer, 2000; Holmstrom & Roberts, 1998; March & Simon, 1958; Schelling, 1960; Simon, 1945).

For us to understand the need for information processing neither task nor agent interdependence (individually or jointly) suffices, as shown in the preceding section. We therefore introduce a new conceptualization of interdependence that helps to precisely identify the need for information processing between agents. This conceptualization has three key elements:

1. For two agents A and B, if the optimal action of each agent depends on a prediction of what the other agent will do, we say that there is *epistemic interdependence* between them.

2. Given epistemic interdependence, for the agents to coordinate their actions requires *predictive knowledge*. A's predictive knowledge about B enables A to act *as if* he could accurately predict B's actions.

3. Predictive knowledge can be formed through information processing activities- communication, mutual observation, learning and (joint) decision making by the agents.

Note that in the text we will continue to consider the case of a dyad of two agents, A and B assigned one task (or cluster of tasks) each. In the technical appendix, we show how to extend the arguments to the general case of n-tasks and m-agents via matrix notation. The construct of epistemic interdependence is valuable because it allows us to see what is common to all coordination problems, irrespective of their surface dissimilarities.[3] The potential for a coordination problem to arise between two agents exists if at least one of the agents requires predictive knowledge about the other. A coordination failure is thus a failure to predict the actions of another in situations where such a prediction is essential for optimal action by oneself. In other words, *a coordination failure occurs when there is epistemic interdependence but the agent(s) do not hold the necessary predictive knowledge.* The agents may possess incomplete or imperfect predictive knowledge so that coordination can be less likely, but not necessarily impossible.

Predictive knowledge and how it is formed is theoretically interesting only because of bounded rationality- an important assumption in our theory. If agents (and the designer) were omniscient, coordination problems would be trivial. Both epistemic interdependence as well as the need for predictive knowledge are the consequences in reality (visible to us, as the modellers) of the choices and actions of the designer and the agents, based on their imperfect knowledge. This analytical approach is identical to that employed in other models of organizations featuring boundedly rational agents – adaptation on rugged landscapes (Levinthal, 1997), exploration-exploitation trade-offs (March 1991), and opportunity identification problems (Davis, Eisenhardt, & Bingham, 2009). In each case, the agents in the model take actions in an environment they do not fully understand or have an imperfect representation of, but both the consequences of the actions and the agent's environment are of course understood by the modeller who constructed it.

The need to predict, rather than the ability to observe another's action can arise either because of sequencing (the other party has not acted yet, or is acting simultaneously with one's own actions) or because of communication and information transmission constraints (which prevents one agent from learning how the other has acted). While the former is salient in empirical accounts of coordination in "real time" settings (surgical teams, fire-fighters- Edmondson, Dillion, Roloff 2007; Weick, 1993), the latter is more often highlighted in descriptions of "realistic time" settings new product development, strategic alliances, post merger integration - Gulati & Singh, 1998; Puranam, Singh, Chaudhuri, 2009. Communication itself can be seen as a coordination problem, as indeed the modern view of linguistics does: when communicating, I need to predict which among several possible meanings you chose to attach to the words you used (e.g. Clark, 1996).

The phrase "as if" is important in the definition of predictive knowledge, because we intend to define it broadly enough to accommodate situations ranging from one in which A acts on the basis of a carefully reasoned prediction about B's actions, as well as those in which through mutual adaptation, A and B have learnt to act as if they are predicting each other's actions successfully (e.g. in the case of inter-personal routines as shown by Cohen & Bacdayan, 1994). Predictive knowledge can be formed in a wide variety of ways -through direct communication, reliance on signals, mutual adjustment to feedback on joint outcomes- all of which constitute information processing activities.[4]

To illustrate epistemic interdependence and predictive knowledge, consider again the unspecialized pin factory in which A and B have to produce 100 pins each, but will only get paid if each agent finishes their order; here, the tasks are independent, but the agents are interdependent to the extent that they face broad incentives. Now, regardless of whether A and B produce the pins at the same time, or sequentially, as long as B does not learn A's output before A finishes her day's work, the scheduling is effectively simultaneous and the agents have to act based on their estimates of the other agent's productivity. Thus there is epistemic interdependence between them and they need to make their decisions on whether to produce their own 100 pins based on their predictive knowledge about the other agent's likelihood of finishing their 100 pins. This need to predict the other agent's output is rooted in their aim to increase their individual rewards. Predictive knowledge in this case can be formed by information processing activities, such as periodic communication regarding each other's progress (in the case of simultaneous actions), or by mutual observations, or on the basis of past experience.

Applied to the consulting firm example above, if team B does not observe the outcome of team A's restructuring efforts before it engages in the design of the new logo, team B will need to engage in information processing, anticipating what level of effort team A is most likely to put in, while A needs to anticipate B's efforts. Note that this example also points to the relative ease of generating the necessary predictive knowledge: if both teams are employed by McKinsey &Co., their information processing requirements may be relatively lower compared to a collaboration between team A from McKinsey and team B from Boston Consulting Group.

Thus, epistemic interdependence helps to precisely identify the circumstances when information processing is necessary between agents in order to form predictive knowledge. This construct is theoretically necessary because neither task nor agent interdependence suffice to explain when information processing is necessary between agents. Our first proposition therefore helps to sharply distinguish epistemic interdependence between agents from interdependence between tasks.

> **Proposition 1:** In a dyad, epistemic interdependence between agents will exist if 1) at least one agent faces broad incentives and 2) the same agent is scheduled to act before knowing the action of the other.

Proposition 1 follows automatically from the definition of epistemic interdependence. In a dyad, there is by definition epistemic interdependence if one agent's optimal action depends on a prediction of the action of another. This situation holds when both the conditions in Proposition 1 are met. In contrast consider the case when either condition is not met. If condition 2 holds but neither agent faces broad incentives, then the rewards to each agent's actions are independent of the other's actions; if condition 1 holds but neither agent acts before knowing (or inferring) the actions of the other, then no prediction is necessary. In this case, there may still be interdependence between agents in the sense that the value of one agent's actions depends on the other's action, but there is no epistemic interdependence, and no particular implications for information processing. *Thus both conditions are independently necessary and jointly sufficient to create epistemic interdependence and the need for information processing between agents*. Proposition 1 also highlights that neither the broad incentives created by reward interdependence (e.g. Kelley & Thibaut, 1978), nor the need for simultaneous actions (i.e. each agent acts before the other's actions are known) generated by bi-directional workflows (e.g. Thompson, 1967) are individually sufficient to create epistemic interdependence and the need for information processing between agents.

It also follows from Proposition 1 that the patterns of task interdependence and epistemic interdependence between agents are identical only in some special cases- more generally the two cannot be assumed to be isomorphic. Trivially, they will be identical if there is no interdependence between tasks or agents, or if task interdependence and epistemic interdependence are both symmetric. However isomorphism is not guaranteed in cases of asymmetry. Suppose that in a dyad of agents A and B performing tasks 1 and 2, only task 2 is dependent on task 1 but not vice versa, i.e. the output of task 1 (which has independent value) is a necessary input to task 2. For isomorphism to hold, B must then be epistemically interdependent with A but not vice versa. This implies that (i) B must face broad incentives *and* be scheduled to act before knowing A's actions, and (ii) A must either face narrow incentives, or be scheduled to act after knowing B's action *or* both (Proposition 1).

INTERDEPENDENCE, INFORMATION PROCESSING & ORGANIZATION DESIGN

Having established the need for the epistemic interdependence construct and defined it, we use it to revisit the basic theoretical links between interdependence, information processing and the design of organizations. Influential contributions by Galbraith and Tushman defined the mapping from increasing levels of interdependence, the resulting task uncertainty and the need for information processing activities (Galbraith, 1973; Tushman & Nadler, 1978). In particular Galbraith elaborated on the concept of task uncertainty as the "difference between the information required to perform a task and the information already possessed" (1973: 5), while Tushman and Nadler's work linked the complexity of tasks as well as the variability of the environment within which the tasks were performed to the extent of task uncertainty- and therefore to the extent of information processing required.

Consistent with these prior approaches, we argue that an organization designer has two basic approaches to ensuring successful coordination among the agents in the system he is designing- he can act either to modify epistemic interdependence between agents, or enable the formation of predictive knowledge between them through information processing (or both). Note that we assume throughout the paper that information processing is used specifically to solve coordination problems; while it might similarly be useful to solve agent-specific competence problems, we only discuss this as a possible extension of the theory in the section on boundary conditions and limitations for the two-agent case. The more general n-task m-agent case of the theory developed in the technical appendix accounts for both these interpretations. In addition, we develop the basic tenets of the theory for an organization in a stable environment. We discuss how to extend our approach to complex and dynamic environments in later sections.

How Epistemic Interdependence Can Be Modified

Organization designers (those individuals explicitly tasked with the goal of improving the performance of the organization) can manipulate epistemic interdependence between agents by varying scheduling and incentive breadth. A designer may be able to convert a simultaneous action schedule into a sequential action schedule, through the use of buffers and inventories (Malone & Crowston, 1994). Further, through superior measurement systems (Zenger & Hesterly, 1997), or the specification of interfaces and design rules (Baldwin & Clark, 2000) a broad measurement situation can be transformed into a narrow measurement situation. Beginning from a situation of broad incentives and simultaneous action, these changes can lead to lower levels of epistemic interdependence (see Proposition 1).

Even if the designer could not measure actions or outputs narrowly or sequence actions, she can choose to allocate *those* tasks that would generate high epistemic interdependence between *different* agents, as clusters of tasks to individual agents. This allows the designer to create lower levels of epistemic interdependence, possibly at the cost of raising the task and cognitive burden of individual agents (Baldwin & Clark, 2000).

These variations in the ability to adjust epistemic interdependence due to variations in task allocation, scheduling and incentive breadth partly reflect differences in *architectural knowledge* (Baldwin & Clark, 2000; Henderson & Clark, 1990; von Hippel, 1990) across organization designers. Colfer and Baldwin define architectural knowledge as "knowledge about the components of a complex system and how they are related" (2010: 2), a definition that builds on Henderson and Clark's (1990) notion of "knowledge about the ways in which the components are integrated and linked together into a coherent whole" (1990: 2). Limited architectural knowledge implies limited comprehension of the task structure - the designer's beliefs can be more coarse-grained than reality (the designer only sees more aggregate clusters of tasks than exist in reality), incomplete (the designer fails to perceive the existence of certain tasks in the task structure) or simply wrong (the designer sees a spurious set of tasks). In turn this limits the ability of the designer to allocate, schedule and reward task performance in a manner that minimizes epistemic interdependence. We formalize this potential consequence of architectural knowledge as follows:

Proposition 2: The *greater* the architectural knowledge of the organization designer, the *lower* the epistemic interdependence between agents can be.

Since an ability to effectively replace broad with narrow incentives is also a result of architectural knowledge, Proposition 2 holds for interdependence between agents in general, and not only for epistemic interdependence, so that linkages between the pattern of task and agent interdependence in general are likely to be weaker when the designer’s architectural knowledge is great. In particular, this proposition explains why (epistemic) interdependence between agents may be adjustable for an architecturally knowledgeable designer, even when interdependence between tasks is not. For instance Levinthal and Warglien (1999) discuss how the designer could transform a complex task-interdependence-landscape into a less-rugged one by imposing a smoother agent-interdependence-landscape.

However, as outlined in Perrow's (1984) work on complex systems as well as Turner's (1976) exposition of organizational and individual failure, architectural knowledge may by no means be common or complete. 'Normal' accidents occur precisely because the designer or the agents do not possess sufficient architectural or predictive knowledge to conceive of all possible contingencies. Similarly, reducing epistemic interdependence does not assume that the remaining necessary predictive knowledge is widespread or perfect. This is why Proposition 2 only states that architectural knowledge *can* be used to lower epistemic interdependence *if* it exists.

How Predictive Knowledge Can Be Formed

A basic tenet of the classical information processing theory of organization design is that modes of organizing differ in their information processing capacities (Galbraith, 1973; Thompson, 1967; Tushman & Nadler, 1978). Consistent with this, we believe it is useful to think of formal organizational structure as *a set of prescribed arrangements that shape the efficiency with which information processing activities by agents help to meet predictive knowledge requirements* (or equivalently, how effective a given amount of information processing activity is in generating predictive knowledge). Choices about organizational structure influence who interacts with whom, as well as the knowledge and skills of the interacting individuals - and therefore enable the formation of predictive knowledge.

To illustrate, consider two fundamental features of any organizational structure- *grouping and linking* arrangements (Chandler, 1962; March & Simon, 1958; Mintzberg, 1979; Nadler & Tushman, 1997). Grouping or departmentalization is a primary means by which the efficiency of intra-group interactions can be enhanced at the expense of the efficiency of inter-group interactions. The efficiency of predictive knowledge formation through information processing in a group can be enhanced by reducing the size and heterogeneity of the group, because communication and coordination quality declines with group size and heterogeneity (Camerer & Knez, 1996; Heath & Staudenmayer, 2000). When groups are collocated, the interaction media is effectively quite rich (Daft & Lengel, 1986). Partitioning an organization into (sub)-groups -units, divisions, departments- is thus a means to enhance the efficiency of information processing activity, and enables the more rapid formation of predictive knowledge *within* those groups.[5]

However, precisely because the efficiency of intra-group information processing declines with group size, not all interdependent agents can be accommodated within the same group. This means that inevitably some arrangements will be needed to manage predictive knowledge requirements across groups. Scholars have proposed that linking mechanisms such as liaison roles, committees, task forces and integrators fulfil this function (Mintzberg, 1979; Nadler & Tushman, 1997). Decisions about grouping units together within common organizational boundaries are different from, and precede in order and importance, non-discrete decisions about the use of "linking" mechanisms between organizational units (Galbraith, 1977; Nadler & Tushman, 1997; Thompson, 1967) - as Nadler and Tushman put it, "The grouping decision made at the top of the organization dictate the basic framework within which all other organizational design decisions [including linking decisions] are made. (...) In short, grouping decisions determine what the organization will be able to do well and deemphasize other work." (1997: 73)"

Thus, the organizational structure shapes the formation of predictive knowledge by prioritizing certain interactions among agents at the expense of others, which is why differences in formal structure matter. We formalize this as follows:

> **Proposition 3**: Formal organizational structures prioritize the formation of predictive knowledge among some agents by emphasizing information processing interactions between them, over interactions with other agents.

Organization Design as the Pursuit of Integration

To make explicit the central normative claim of the information processing literature, the goal of an organization designer may be viewed as enhancing gains from coordination despite the information processing constraints of individuals and the differentiation that results from specialization (Galbraith, 1973; Lawrence & Lorsch, 1967; March & Simon, 1958; Tushman & Nadler, 1978). Equivalently, we may say that for a given allocation of tasks to agents, the designer's goal is to enhance the degree of ***integration*** in the organization, defined by Lawrence and Lorsch as "the quality of the state of collaboration that exists among departments that are required to achieve unity of effort by the demands of the environment." (1967: 11). We translate this term in the context of this paper as the joint probability that all agents in an organization have the necessary predictive knowledge. We argue that a greater probability of coordination failures is equivalent to a lower degree of integration. To keep the exposition simple and retain focus on information processing, we make the assumption here that the agents have aligned incentives– in other words integration between agents would be achieved in the absence of coordination failures. In the section on the boundary conditions, we note how this assumption can be relaxed, and cases of incentive misalignment can be incorporated in our theory.

In the case of two agents A and B in which each is epistemically interdependent with the other, the degree of integration is the multiplication of the probabilities that A has predictive knowledge about B (p_{AB}), and B has predictive knowledge about A (p_{BA}). One approach to increasing integration consists of reducing epistemic interdependence between the agents, so that only one or neither agent needs predictive knowledge about the other. This is equivalent to setting p_{AB} and/or p_{BA} equal to 1. Integration will then depend on only one probability or none, so that reducing epistemic interdependence effectively increases the degree of integration (because probabilities are less than 1). This suggests that an organization designer with superior architectural knowledge could improve overall integration by reducing the epistemic interdependence among agents (Proposition 2). A second approach to enhancing integration lies in specifying a pattern of interactions among the agents through an organizational structure (see Proposition 3) that will improve predictive knowledge (i.e. increase the probabilities p_{AB} and p_{BA}). Thus,

> **Proposition 4***:* For a given allocation of tasks, the degree of integration in an organization may be improved a) either by reducing epistemic interdependence among its agents, or b) selecting an organizational structure to enhance information processing interactions among its epistemically interdependent agents (or both).

Integration in an organization can therefore be enhanced either by reducing epistemic interdependence, or by ensuring the formation of predictive knowledge through information processing.

Proposition 4 has several powerful implications. First, it explains *why* functional equivalence may be so common across organization designs (Gresov & Drazin, 1997; Merton, 1967). The nature of this equivalence in terms of integration can be understood at different conceptual levels. As Proposition 4 notes, for a given allocation of tasks, comparable degrees of integration can be achieved either by modifying epistemic interdependence between agents or interactions between them. At the most fundamental level, this in turn is equivalent to saying that integration can be achieved either with high architectural knowledge of the designer, or high predictive knowledge among the agents. For this reason, organization design may be seen as the interplay between the designer's knowledge of how to divide and allocate tasks (architectural knowledge) and the agents' knowledge of how to integrate tasks (predictive knowledge). The functional equivalence in terms of integration of various combinations of architectural and predictive knowledge is shown in Figure 1. For a given allocation of tasks, this functional equivalence also translates into equi-final performance outcomes.

Insert Figure 1 about here

Second, while Proposition 1 alone shows that tasks and epistemic interdependence are not necessarily isomorphic, Proposition 4 in combination with Propositions 1 and 3 also explains *why* isomorphism between the structure of tasks and the structure of organizations may be rare. The same allocation of tasks can generate different epistemic interdependence patterns between agents (Proposition 1); different patterns of epistemic interdependence can produce the same level of integration in conjunction with different organizational structures (Proposition 3). Therefore, even when faced with the same set of tasks, widely varying organizational structures may have identical levels of integration (Proposition 4). Mirroring between task interdependence and organizational structures may therefore be a special case, rather than what we would expect by default (Colfer & Baldwin, 2010).

Third, with imperfect integration (i.e. the joint probability of the agents possessing the required predictive knowledge is less than 1), exceptions and errors of coordination will arise. Therefore additional provision to manage the exceptions that inevitably occur must be made separately - through hierarchical dispute resolution, or the presence of slack, for instance (Galbraith, 1977; Tushman & Nadler, 1978). Thus as shown in Figure 1, the need for exception management should decrease as either architectural or predictive knowledge increase. Alternatively, slack or increased fault tolerance are means by which organizations may be able to cope with low levels of integration.

Fourth, because both architectural knowledge (and therefore epistemic interdependence) as well as predictive knowledge can vary with time, Proposition 4 can also be useful to theorize about changes over time to organizational structures. We believe it is plausible that both predictive knowledge among agents and the architectural knowledge of the organization designer increase over time through repeated interaction (Daft & Lengel, 1984; 1986). We do not assume that either the agents or the designer are mindless instruments of the production process, so that as a history of interactions builds up, the predictive knowledge of the agents about each other should improve through the development of habits, conventions, precedents, norms, and shared language (Arrow, 1974; Clark, 1996; March & Simon, 1958). Architectural knowledge is also known to accumulate with experience in a technological system (von Hippel, 1990). Proposition 4 therefore suggests a tendency towards greater integration over time for any given allocation of tasks. It also suggests that organizations with identical tasks but different histories may be characterized by diverse, functionally equivalent organization designs.

IMPLICATIONS FOR RESEARCH

We examine how the distinction we have developed between task and agent interdependence, and the theoretical refinements we propose on the basis of this distinction (Propositions 1- 4) may be useful in framing further research on organization designs. Note that the empirical predictions we make using epistemic interdependence theory in this section are naturally bounded by the assumption of 'all else being equal'.

The Choice of Coordination Mechanisms

The classical literature on organization design has devoted considerable attention to the simplest organizational element that underlies complex organizations- a dyad of interdependent units (divisions, departments, teams, individuals) along with a supervisor who has authority over the units. At this micro-structural level, there are three broad classes of mechanisms by which activities across the interdependent units are coordinated: "programming" (or planning) entails the standardization of work and output, whereas "feedback" (or mutual adjustment) involves improving the effectiveness of communication (Galbraith, 1973; March & Simon, 1958; Thompson, 1967). "Hierarchical supervision" (or referral) - is the means by which the exceptions arising from the limitations of programming and feedback are managed (Mintzberg, 1979; Tushman & Nadler, 1978).

While there is broad agreement in the literature on the basic types of coordination modes -programming, feedback and hierarchical supervision- there is less consensus on the conditions under which one is preferred to the others. Different theorists have suggested distinct drivers of the choice of coordination modes - including the stability of the task structure (March & Simon, 195: 182), the complexity of task interdependence (Thompson; 1967) and the extent of task uncertainty (Galbraith, 1973).

The epistemic interdependence approach suggests a novel means of looking at the problem. In essence, reducing epistemic interdependence or increasing predictive knowledge among agents mirrors the programming versus feedback dichotomy. As Proposition 4 states, integration increases with both architectural knowledge and predictive knowledge. However, there is an important asymmetry between these paths to improving integration. The improvement of predictive knowledge between agents can never improve integration beyond what is achieved by eliminating epistemic interdependence between them. This is because the removal of epistemic interdependence is equivalent to setting the probability of the relevant agent possessing predictive knowledge to 1, whereas improving the information structure via the organizational architecture can only lead to an improvement in this probability, which will typically remain less than 1. The difference is more striking as the number of agents increases, as more terms will be multiplied; the larger the number of fractions being multiplied, the smaller the impact of a change in any one of them.

This suggests several testable implications: First, since both architectural and predictive knowledge may increase over time in a stable environment, we would expect that the passage of time should weaken the empirical relationships between the task interdependence and organizational structures (Propositions 2, 3, 4). Thus researchers should look for the moderating role of organizational age in tests of relationships between task interdependence and coordination mechanisms.

Second, the choice of coordination mode –programming vs. feedback- should rest on the extent of the designer’s architectural knowledge vis-à-vis the ease of forming predictive knowledge among the agents, rather than task interdependence per se (Propositions 2, 3 and 4). When either architectural or predictive knowledge is limited, we should expect to see a decisive shift towards the alternative mode of coordination (Proposition 4).

Architectural knowledge is unlikely for novel and poorly understood task architectures (Adler, 1995; Baldwin & Clark, 2000; von Hippel, 1990). Thus programming is unlikely to be useful as an approach to coordinating tasks poorly understood by the designer. Predictive knowledge is harder to form when there are constraints on communication and interaction between agents - the ease of forming predictive knowledge will depend on the richness of the communication media available, e.g. face-to-face communication is more effective than text in generating the necessary predictive knowledge when the information transmitted is ambiguous and needs to overcome different frames of references (Daft & Lengel, 1986). For instance, researchers should expect to see less reliance on programming when collocation of agents is feasible. The formation of predictive knowledge may also be impaired by properties of knowledge that makes its exchange difficult (see for instance, Szulanski, 1996). Thus researchers should expect to find greater reliance on programming when there are motivational or cognitive constraints on knowledge sharing between agents.

Third, all else being equal, there should also be a bias towards reliance on programming rather than feedback as organization size increases. This is based on the observation that eliminating epistemic interdependence will be even more beneficial than improving predictive knowledge as the organization increases in size (because the multiplications of many fractions diminishes the impact of changes to on or a few of them). Thus, epistemic interdependence theory proposes a mechanism to account for the positive association between size and formalization.

The third coordination mechanism - exception management - is one of dispute resolution at a higher hierarchical level (e.g. Galbraith, 1973; Simon, 1962). Given that the exceptions have to be handed upward until a point where a common superior has sufficient information and authority to solve the issue, and because it consumes time and attention, this mechanism is costly. When exceptions -disagreements, misunderstanding, disputes- arise because of coordination failures between agents, their hierarchical superior may resolve these exceptions by improving the predictive knowledge of each agent, or simply by exercising authority and imposing a solution (which may not necessarily be perfect). Thus, researchers should find reliance on exception management is likely to be most significant when both architectural and predictive knowledge are limited (see Figure 1).

The Span of Control

The span of control has historically been thought of as the number of direct subordinates a manager supervises. [6] The span of control plays an important role in shaping other properties of the organizational macrostructure such as centralization, formalization and the number of levels of reporting (Mintzberg, 1979) and understanding its determinants should shed light on questions of when and why there might be design variations at different layers of the hierarchy. If the span of control increases exogenously, the pressures to delegate decision making to subordinates or formalize –rely more on programming- increases due to the limits of supervisory capacity (Gittell, 2001; Mintzberg, 1979). If the feasible span of control at all levels -the number of subordinates a manager can supervise effectively- increases, then for a fixed number of employees, we would expect to see fewer layers in the organization (Colombo & Delmastro, 2007).

The evidence to date on the determinants of the span of control has not been encouraging. For instance, Entwisle and Walton (1961) reported the somewhat surprising finding that the span of control did not appear to vary much across types of organizations (colleges vs. businesses) or by size. Woodward (1965) found that the span of control varied by the technology of production - which could vary both across and within organizations: "In direct contrast to the span of control of the chief executive, which grew larger with technical advance, spans of control at middle management levels grew smaller." (1965: 53). Dewar and Simet (1981) observed that while the determinants of the span of control did appear to vary by levels in the organization, on the whole their data did not "resolve the controversy as to whether size or technology [two important competing explanations] is the primary cause of spans; in this data neither seems to be." (1981: 21).

Looking beyond the challenges in measuring these variables reliably, the epistemic interdependence approach may help to clarify why we see weak empirical results for the determinants of the span of control. Consider a manager with m subordinates. We assume that the capacity of the manager to handle exceptions and support subordinates is limited, because of the usual bounded rationality considerations (Simon, 1945). The number of subordinates who can be hierarchically supervised (i.e. span of control) therefore increases either (1) if the subordinates generate fewer exceptions, or (2) if the supervisor has greater exception management capacity, or both.

It follows immediately, that the greater the degree of integration among the subordinates, the greater the feasible span of control for the manager. As we know, integration increases with both architectural knowledge of the designer (not necessarily the manager) as well as predictive knowledge of the agents (Proposition 4) - so that the span of control in the administrative hierarchy should increase with both kinds of knowledge (and possibly with time, if both forms of knowledge increase over time). This allows us to make sense of Udell's (1967) findings who found "a positive relationship between the span of control and similarity of functions supervised, geographic dispersion, the use of personal assistants, subordinates' years of experience on the job, and the amount of supervision subordinates receive from others." (1967: 438). While most of these findings are intuitive given our theory, the positive relationship between geographical dispersion and the span of control is somewhat puzzling, as geographic distance should make predictive knowledge harder rather than easier to form among the subordinates. (Udell points out that this result is not driven by enhanced formalization,) Our view is that this is due to the strong (negative) correlation between 'dissimilarity of functions' and 'geographic dispersion' (-0.734 as reported in Table 5, Udell, 1967: 434) - i.e. those subordinates that had a common supervisor and were geographically dispersed were perhaps functionally similar by design, facilitating the manager's task by increasing the predictive knowledge of the agents and thus minimizing the number of exceptions they generated.

The Impact of the Organization's Environment

The attributes of an organization's environment -comprising the organization's consumers and users, suppliers, competitors, and regulatory groups- are believed to pose important contingencies in organization design (Mintzberg, 1979). A fair number of environmental attributes relevant to a firm's decision-making process have been proposed and analyzed. These include environmental uncertainty (Donaldson, 2001: 22), velocity (Eisenhardt & Bourgeois, 1988), equivocality (Daft & Lengel, 1986: 567), and hostility (Burton & Obel, 1998: 171).

As several scholars have argued (Burton & Obel; 1998; Galbraith 1973, 1977; Mintzberg, 1979), the impact of environmental attributes can be traced through their impact on information processing within the organization. Consistent with this work, we argue that the consequences of the various forms of environmental change can ultimately be analyzed in terms of the impact on information processing, and that propositions 1-4 are sufficient to understand these impacts in epistemic terms. Following Duncan (1972) and Mintzberg (1979), we distinguish between complexity of the environment at a point in time, and the dynamism (or rate of change) of the environment.

Complex environments may be thought of as those characterized by limited architectural knowledge or constraints on predictive knowledge formation – limits to the designers and the agents knowledge, respectively. Perrow (1967) and Adler (1995) have both offered specific measures of the complexity of the task environment that prevent a deep architectural understanding from being achieved. These limits to architectural understanding and predictive knowledge should have predictable influences on integration for the reasons outlined in Propositions 2 and 4. Therefore in more complex environments, researchers should expect that epistemic interdependence between agents should be higher and the degree of integration in the organization should be lower. As a corollary, empirical tests should also reveal that the span of control should be smaller, and delegation should be greater in administrative hierarchies when the environment is complex. One may also expect to see organizations investing in information technologies to improve predictive and architectural knowledge in such environments, and this has indeed been documented (e.g. Kobelsky, Richardson, Rodney & Zmud, 2008).

In contrast, the dynamism of the environment can be related to *shocks* to the designer's architectural knowledge and/or the agents' predictive knowledge. Frequent reductions in architectural knowledge –due to rapid technological or business innovations- suggest that a design strategy based on reducing epistemic interdependence is unlikely to be viable. This places the burden instead on predictive knowledge formation by each agent (see Proposition 4) with as many other agents as possible- because *who* any one agent is epistemically interdependent with, may change. Frequent reductions in predictive knowledge in contrast –through turnover, for instance- suggest the need for organizational structures that enable the swift rebuilding of predictive knowledge. Thus researchers should expect to see that dynamic environments may result in a reduced emphasis on modifying epistemic interdependence or an increased emphasis on stabilizing organizational structures, depending on the precise nature of the dynamism.

BOUNDARY CONDITIONS & LIMITATIONS

Bounded Rationality

Our approach to theorizing about organization design has been anchored in the information processing perspectives first developed in the Carnegie school (March & Simon, 1958). The assumptions of bounded rationality is pervasive not only in our work, but in the literature on information processing in general. This assumption is critical since a perfectly knowledgeable agent (with no cognitive or communication restrictions) will face no coordination problems. In the context of our theory, such omniscient designers and agents would result in zero epistemic interdependence between agents who would face no cognitive limits to the number of tasks feasibly assigned to them.

Incentive Alignment

Another assumption we make throughout the paper is that the agents do not face conflicting incentives – that as long as they have predictive knowledge, integration will be perfect. We acknowledge an important alternative tradition that focuses on the challenge of aligning interests to explain organization designs. In this perspective, managing interdependence can be complicated when the initial (i.e. pre-design) distribution of gains from interdependent actions creates diverging interests - for instance, because of asymmetric dependence resulting in power imbalances, incentives to free ride or hold-up. This approach characterizes the extensive literature on social dilemmas (Kollock, 1998), reward interdependence within teams (Kelley & Thibaut, 1978), power (Emerson, 1962; Pfeffer & Salancik, 1978), principal-agent models with multiple agents (Holmstrom, 1982), and hold-up problems (Grossman & Hart, 1986; Williamson, 1975). These diverse accounts from sociology, social psychology and economics have in common the notion that the central organizational design problem involves using incentives (formal or informal, non-monetary or monetary) to change the distribution of gains from managing interdependence in a manner that motivates optimal (if not efficient) actions by interdependent actors.

Incentive structure does play a critical part in our approach through the notion of incentive breadth, but we are largely agnostic to the problem of fashioning binding incentive agreements on the distribution of gains in interdependent tasks. Thus we ignore issues such as participation constraints, ex post reneging, opportunistic bargaining, and misrepresentation by agents Such considerations can however be represented in a "reduced form" within our framework, by replacing "is epistemically interdependent" with "needs to work collaboratively". In this case, the degree of integration achieved by the organization can be interpreted as the joint probability of all agents being able to work collaboratively with those they are interdependent with. Such reduced form analysis may prove fruitful to analyse aggregate rather than dyadic impacts of incentive misalignment.

Information Processing for Coordination

Information processing activities are not restricted to solving coordination problems; agents performing individual tasks also process information. To keep our arguments clear, we have ignored this possibility in the paper. However, in the technical appendix we show that in the matrix representation of the m-agent case, the diagonals naturally correspond to intra-agent information processing, and that computations of the degree of integration can take these readily into account.

Stable Environments

Finally, we develop much of the theory based on the assumption of a stable environment. While this is a simplifying assumption that helps to focus on the core arguments in Propositions 1 to 4, we have also discussed the consequences of dynamic environments in the section on the 'Impact of the Organization's Environment' above.

CONCLUSION

By drawing a clear distinction between inter-task and inter-agent interdependence, we have constructed an analytical framework that can help to refine our understanding of the links between interdependence, information processing, and organization design.

The epistemic interdependence theory we develop helps to explain why interdependence between agents can be endogeneous, why organization structures may not mirror task interdependencies, and why organizations facing identical sets of tasks may have different, equally effective organizational structures. Applying our logic to a diverse set of examples ranging from micro- to macro-levels throughout the theory development of this paper, we have shown how the concepts apply to a wide variety of settings - from a pure manufacturing context to the more complex, knowledge-intensive task of coordinating joint ventures and consulting projects, and product development within firms. We have touched upon several topics central to the study of organization design but we recognize that our coverage of topics is hardly exhaustive. Rather, the goal in this paper has been to demonstrate the promise of a new approach to tackling these classic problems through a few initial steps. We hope to be joined by others in taking many more.

FOOTNOTES

[1] The dual focus on specifying the analytical structure of underlying coordination problems as well as the resulting implications for information processing make our approach distinct from earlier attempts at analyzing organization design within the information processing perspective. For instance, unlike Malone and Crowston (1994), we focus on the structure of the underlying coordination problem associated with different ways to divide labor rather than the process of coordination, and unlike Weber (2004) we also go beyond characterizing the underlying coordination problems to specifying the implications for information processing and the choice of organizational structures.

[2] The reason why it is difficult to observe these differences between agent and task interdependence at the inter-firm level is due to the fact that it is difficult to decouple the value to the agent from the value to a system designer when the firm is the agent.

[3] The traditional usage of the term "interdependence" in the organization design literature encompasses both one-sided and two-sided dependence. Further, we note that there is another sense in which the term "epistemic dependence" is used - by epistemologists to signify the dependence of the non-expert on the expert (e.g. Hardwig, 1985). Therefore at some expense of precision but gain in economy of expression, we will use the term epistemic interdependence for both one and two sided dependence.

[4] When coordinated action arises from shared knowledge, it may also be of interest to understand exactly to how many orders knowledge must be shared for coordinated action. This is a question central to the research in epistemic game theory (e.g. Aumann & Brandenburger, 1995), but one which we are agnostic about in this paper.

[5] Because membership in a group is also defined by deference to a common source of authority, grouping also helps to manage the exceptions that inevitably arise (in contrast, it may be necessary to climb several layers of the hierarchy to find a common boss to resolve inter-group exceptions).

[6] Note that the span of control appears to connote only the manager's *formal* authority - in today's business context, “span of responsibility” might be a more appropriate term to capture the managers' zone of influence. In the interests of preserving continuity with prior literature, we use the span of control terminology but imply the broader sense.

TECHNICAL APPENDIX

To generalize Propositions 1- 4 first to the two agent n-task case, it suffices to note that nothing changes in the arguments if we make A and B "clusters of non-overlapping tasks" rather than individual tasks (an overlapping task can be recast as two non-overlapping but interdependent tasks).

To analyze the relationships between information processing and organization design for the general case of n-tasks and m-agents, we define four binary matrices as below. Note that each matrix captures an aspect of objective reality, but neither the designer nor the agent may be aware of these. Rather, the matrices we describe below help to capture the consequences in reality (visible to us, as the modellers) of the choices and actions of the designer and the agents based on their imperfect knowledge.

1. Let the n X n binary matrix T^R represent the ***underlying task structure***- the true underlying pattern of interdependence between tasks, where a "1" in a cell denotes that 'column task' is dependent on 'row task'. The elements of this matrix are represented by r_{ij}, and r_{ii}=1 (each task is dependent on itself).

2. Let the ***allocated task structure*** be represented by the m X m binary matrix T^A where a "1" in a cell denotes that 'column agent's allocated cluster of tasks' is dependent on 'row agent's allocated cluster of tasks'. The elements of this matrix are represented by a_{ij}, and a_{ii}=1 (each agent's task cluster is dependent on itself).

3. Let the pattern of epistemic interdependence between agents- the ***epistemic structure***- be represented by an m X m binary matrix E, whose elements are denoted by e_{ij}. Here e_{ij} =1 if agent j requires predictive knowledge about agent i, else e_{ij} =0, and e_{ii} =1 (each agent needs predictive knowledge about himself).

4. Finally, define the ***information structure*** I_t at time t as an *m X m* binary matrix, whose elements $p_{i,j,t}$ represent the probability that agent j has predictive knowledge about agent i at time t ($p_{i,i,t}$ may be interpreted as the probability that the agent has the knowledge necessary to undertake her own task). When $p_{i,j,t}$ = 1 for the corresponding non-zero elements in E (i.e. if $p_{i,j,t}$ = 1 for $e_{i,j} = 1$), we can say with certainty that the predictive knowledge requirements of j with respect to i have been met.

underlying Task Structure

$$T^R = \begin{bmatrix} 1 & 1 & 0 & \cdots & 0 \\ 1 & 1 & 1 & & \\ 0 & 0 & 1 & & \\ \vdots & & & \ddots & \\ 1 & & & & 1 \end{bmatrix}_{n\,X\,n}$$

allocated Task Structure

$$T^A = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 1 & & \\ 1 & 0 & 1 & & \\ \vdots & & & \ddots & \\ 0 & & & & 1 \end{bmatrix}_{m\,X\,m}$$

Epistemic Structure

$$E = \begin{bmatrix} 1 & 0 & 1 & \cdots & 0 \\ 0 & 1 & 0 & & \\ 0 & 0 & 1 & & \\ \vdots & & & \ddots & \\ 0 & & & & 1 \end{bmatrix}_{m\,X\,m}$$

Information Structure

$$I_t = \begin{bmatrix} 1 & 0.2 & 0.8 & \cdots & 0.1 \\ 0.5 & 1 & 0.4 & & \\ 0.7 & 0 & 0.9 & & \\ \vdots & & & \ddots & \\ 1 & & & & 1 \end{bmatrix}_{m\,X\,m}$$

Note that while T^A, E and I_t result from the actions of the organization designer and the agents, we do not assume that they have accurate representations of any of these matrices or indeed of T^R.

Generalizing Propositions to the n-Task m-Agent Case

Proposition 1: An epistemic structure for *m* agents is an aggregation of *(m)(m-1)* dyadic epistemic structures. Thus in the general n-task, m-agent case, there may be no interdependence in the epistemic structure (E) even if it exists in the allocated task structure (T^A) and vice versa.

A special case is noteworthy: if only the output of the entire task structure can be measured (e.g. if the tasks are design tasks, and only overall product performance is rewarded) then *E* will be the transpose of T^A

Proposition 2: Define L_t as the number of all non-zero elements in E at time t.

$$L_t = \sum_{i=1}^{m} \sum_{j=1}^{m} e_{i,j,t} \tag{1}$$

A scalar metric of the extent of epistemic interdependence is then given by $EI_t = L_t - m$.

Limited architectural knowledge implies limited comprehension of T^R- which limits the ability of the designer to allocate, schedule and reward task performance in a manner that minimizes epistemic interdependence. Greater architectural knowledge therefore potentially leads to lower L_t and therefore lower EI_t.

Proposition 3: How effective an organization structure has been at meeting the predictive knowledge requirements stipulated by an epistemic structure can be gauged through its degree of integration (ρ_t) defined as the product of the $L_t \leq m^2$ elements from I_t for which the corresponding elements in E $e_{i,j} = 1$. The degree of integration of the organization at time *t* can thus be written as

$$\rho_t = \prod_{i=1}^{m} \prod_{j=1}^{m} \delta p_{i,j,t} \tag{2}$$

where $\delta = 1$ if $e_{i,j} = 1$ (there will be L_t such terms in E as captured in equation 1). Integration, or rather its complement (1-ρ_t), offers a useful index of the probability of exception occurrence.

Proposition 4: For a given T^A, define the *Value* of the organization as

$$V_t = \varphi \rho_t \tag{3}$$

where φ denotes the gains from integration for that T^A – the magnitude of the value of the organization for a given task allocation with complete predictive knowledge among the agents (i.e. if $p_{i,j,t}$ = 1 for $e_{i,j} = 1$). Clearly if architectural knowledge is poor, to the extent that some tasks in T^A are spurious (not present in T^R) or missing in the task structure (present in T^R but not in T^A), φ is lower. However, for a given task allocation (and hence φ) the goal of organization design can be reformulated as enhancing ρ_t.

There are two generic ways to do this: the first approach to increasing ρ_t involves reducing epistemic interdependence: equation (2) features the product of L_t probabilities, so that reducing L_t effectively increases integration (because probabilities are less than 1). This suggests that an organization designer with superior architectural knowledge could improve the gains from integration by reducing the epistemic interdependence among agents (reduce L_t in equation 1). A second approach to enhancing integration lies in specifying a pattern of interactions among the agents (i.e. an organizational structure) that will lead to the creation of an I_t (and therefore high values of $p_{i,j,t}$) to meet the requirements stipulated by E.

REFERENCES

Adler, P.S. 1995. Interdepartmental Interdependence and Coordination: The Case of the Design/Manufacturing Interface. ***Organization Science***, 6(2): 147-167.

Argyres, N.S. 1995. Technology strategy, governance structure and interdivisional coordination. ***Journal of Economic Behavior and Organization,*** 28(3) 337–358.

Arrow, K.J. 1974. ***The Limits of Organization.*** New York: WW Norton & Company.

Aumann, R. & Brandenburger, A. 1995. Epistemic Conditions for Nash Equilibrium. ***Econometrica,*** 63(5): 1161-1180.

Baldwin, C.Y., & Clark, K.B. 2000. ***Design Rules***. Cambridge, MA: The MIT Press.

Barley, S.R. 1986. Technology as an Occasion for Structuring: Evidence from Observations of CT Scanners and the Social Order of Radiology Departments. ***Administrative Science Quarterly*** 31(1): 78-108.

Burton, R.M., & Obel, B. 1998. with contributions by S.D. Hunter III., M. Sondergaard, and D. Dojbak. ***Strategic Organizational Diagnosis and Design: Developing Theory for Application*** (2nd ed.). Boston/Dordrecht/London: Kluwer Academic Publishers.

Burton, R.M., & Obel, B. 1984. ***Designing Efficient Organizations: Modelling and Experimentation***. Amsterdam: North-Holland.

Camerer, C. 2003. ***Behavioural Game Theory: Experiments in Strategic Interaction***. Princeton: Princeton University Press.

Camerer, C. & Knez, M. 1996. Coordination, Organizational Boundaries and Fads in Business Practices. ***Industrial and Corporate Change,*** 5(1): 89-112.

Capon, N., Farley, J.U. & Hoenig, S., 1990. Determinants of financial performance: a meta-analysis. ***Management Science***, 36(10), p.1143-1143.

Chandler, A.D. Jr. 1962. ***Strategy and Structure.*** Cambridge, MA: MIT Press.

Clark, H. 1996. ***Using Language***. Cambridge, UK: Cambridge University Press.

Cohen, M.D. & Bacdayan, P. 1994. Organizational Routines are Stored as Procedural Memory: Evidence from a laboratory study. ***Organization Science,*** 5(4): 8-13.

Colfer, L. & Baldwin, C.Y. 2010. ***The Mirroring Hypothesis: Theory, Evidence and Exceptions***. Working Paper No. 10-058, Harvard Business School, Cambridge, MA.

Colombo, M.G. & Delmastro, M. 2007. ***The Economics of Organizational Design: Theoretical insights and empirical evidence***. New York: Palgrave Macmillan.

Daft, R.L., & Lengel, R.H. 1984. Information Richness: A New Approach to Manager Information Processing and Organization Design in *Research in Organizational Behavior,* B. Staw and L. L. Cummings (Eds.), JAI Press, Greenwich, Connecticut.

Daft, R.L., & Lengel, R.H. 1986. Organizational Information Requirements, Media Richness and Structural Design. ***Management Science***, 32(5): 554-572.

Dalton, D.R., Todor, W.D., Spendolini, M.J., Fielding, G.J., Porter, L.W. 1980. Organization Structure and Performance: A critical review. ***Academy of Management Review***, 5(1): 49-64.

Davis, J.P., Eisenhardt, K.M., Bingham, C.B. 2009. Optimal Structure, Market Dynamism, and the Strategy of Simple Rules. ***Administrative Science Quarterly***, 54:413-452.

Dewar, R.D. & Simet, D.P. 1981. A Level Specific Prediction of Spans of Control Examining the Effects of Size, Technology, and Specialization. ***Academy of Management Journal,*** 24(1): 5-24.

Donaldson, L. 2001. ***The Contingency Theory of Organizations***. Thousand Oaks, CA: Sage

Doty, D.H., Glick, W.H., & Huber, G.P. 1993. Fit, Equifinality, and Organizational Effectiveness: A test of two configurational theories. ***Academy of Management Journal***, 36(6): 1196-1250.

Drazin, R. & Van de Ven, A. H. (1985). "Alternative Forms of Fit in Contingency Theory."

Administrative Science Quarterly 30(4): 514-539.

Dunbar, R.L.M. & Starbuck, W.H. 2006. Learning to design organizations and learning from designing them. ***Organization Science*** 17(2): 171-178.

Duncan, R.B. 1972. Characteristics of Organizational Environments and Perceived Environmental Uncertainty. ***Administrative Science Quarterly***: 313-327.

Edmondson, A, Dillon, J., Roloff, K.S. 2007. Three Perspectives on Team Learning Outcome Improvement, Task Mastery, and Group Process. ***Academy of Management Annals***, 1: 269-314.

Eisenhardt, K.M., & Bourgeois III, L.J. 1988. Politics of Strategic Decision Making in High-Velocity Environments: Toward a Midrange Theory. ***Academy of Management***

Emerson, R.M. 1962. Power-Dependence Relations. ***American Sociological Review***, 27(1): 31-41.

Entwisle, D.R. & Walton, J. 1961. Observations on the Span of Control. ***Administrative Science Quarterly,*** 5(4): 522-533.

Eppinger, S.D. 1991. Model-based Approaches to Managing Concurrent Engineering. ***Journal of Engineering Design,*** 2: 283-290.

Ethiraj, S.K. & Levinthal, D.A. 2004a. Bounded Rationality and the Search for Organizational Architecture: An evolutionary perspective on the design of organizations and their evolvability. ***Administrative Science Quarterly***, 49 (3): 404-437.

Ethiraj, S.K. & Levinthal, D.A. 2004b. Modularity and Innovation in Complex Systems. ***Management Science,*** 50(2): 159-173.

Galbraith, J. R. 1977. ***Organizational Design***. Reading, MA: Addison-Wesley.

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

Gittell, J.H. 2001. Supervisory Span, Relational Coordination, and Flight Departure

Performance: A reassessment of postbureaucracy theory. ***Organization Science,*** 12(4): 468-483.

Grant, R.M. 1996. Toward a knowledge based theory of the firm. ***Strategic Management Journal,***, 17: 109-122.

Gresov, C. & Drazin, R. 1997. Equifinality: Functional Equivalence in Organization Design. ***Academy of Management Review*** 22(2): 403-428.

Grossman, S.J. & Hart, O.D. 1986. The Costs and Benefits of Ownership: A theory of vertical and lateral integration. ***Journal of Political Economy,*** 94(4): 691-719.

Gulati, R. & Singh, H. 1998. The Architecture of Cooperation: Managing coordination costs and appropriation concerns in Strategic Alliances. ***Administrative Science Quarterly,*** 43(4): 781-814.

Hannan, M.T. & Freeman, J. 1977. The Population Ecology of Organizations. ***American Journal of Sociology*** 82(5): 929-964.

Hardwig, J. 1985. Epistemic Dependence. ***The Journal of Philosophy,*** 82(7): 335-349.

Heath, C., & Staudenmayer, N. 2000. Coordination Neglect: How Lay theories of organizing complicate coordination in organizations. ***Research in Organizational Behavior,***, 22(53-191.).

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

Holmstrom, B. 1982. Moral hazard in teams. ***Bell Journal of Economics***, 13(2): 324-340.

Holmstrom, B., & Roberts, J. 1998. The Boundaries of the Firm Revisited. ***Journal of Economic Perspectives***, 12(4): 73.

Kelley, H.H., & Thibaut, J.W. 1978. ***Interpersonal Relations: A Theory of Interdependence***. New York: John Wiley & Son.

Kobelsky, K., Richardson, V.J., Smith, R.E., Zmud, R.W. 2008. Determinants and Consequences of Firm Information Technology Budgets, ***The Accounting Review***, 83(4): 957-995

Kollock, P. 1998. Social Dilemmas: The Anatomy of Cooperation. ***Annual Review of Sociology***, 24(1): 183.

Kretschmer, T., & Puranam, P. 2008. Integration through Incentives in Differentiated Organizations. ***Organization Science.***, 19(6): 860-875.

Lawrence, P.R., & Lorsch, J.W. 1967. ***Organization and Environment: Managing Differentiation and Integration.*** Boston: Harvard Graduate School of Business Administration.

Levinthal, D. A. 1997. Adaptation on Rugged Landscapes. ***Management Science,*** 43(7): 934.

Levinthal, D.A. & Warglien, M. 1999. Landscape Design: Designing for Local Action in Complex Worlds. ***Organization Science***, 10: 342-357.

Malone, T.W. & Crowston, K. 1994. The Interdisciplinary Study of Coordination. ***ACM Computing Survey,*** 26(1)

March, J.G. 1991. Exploration and Exploitation in Organizational Learning. ***Organization Science***, 2(1): 71-87.

March, J.G., & Simon, H.A. 1958. ***Organizations***. Cambridge, MA: Wiley.

Merton, R.K. 1967. ***On Theoretical Sociology,*** New York: Free Press.

Meyer, J.W. & W.R. Scott 1983. ***Organizational Environments: Ritual and Rationality***, Beverly Hills, CA: Sage.

McCann, J.E. & Ferry, D.L. 1979. An Approach for Assessing and Managing Inter-Unit Interdependence. ***Academy of Management Review,*** 4(1): 113-119.

Milgrom, P. & Roberts, J. 1990. The economics of modern manufacturing: Technology, strategy, and organization." ***American Economic Review*** 80(3): 511-28.

Milgrom, P. & Roberts, J. 1995. Complementarities and Fit Strategy, Structure, and Organizational Change in Manufacturing. ***Journal of Accounting and Economics,*** 19(2-30): 179-208.

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

Mohr, L.B. 1971. Organizational Technology and Organizational Structure. ***Administrative Science Quarterly,*** 16(4): 444-459.

Nadler, D.A., & Tushman, M.L. 1997. ***Competing by Design: The Power of Organizational Structure***. Oxford, UK: Oxford University Press.

Perrow, C. 1967. A Framework for the Comparative Analysis of Organizations. ***American Sociological Review***, 32: 194-208.

Perrow, C. 1984. ***Normal Accidents: Living with high-risk technologies***. New York: Basic Books.

Pfeffer, J. & Salancik, G.R. 1978. ***The External Control of Organizations: A Resource Dependence Perspective***. New York: Harper & Row.

Puranam, P., Singh, H., & Chaudhuri, S. 2009. Integrating acquired capabilities: When structural integration is (Un)Necessary. ***Organization Science.***, 20(2): 313-328.

Schelling, T. 1960. ***The Strategy of Conflict***. Cambridge, MA: Harvard University Press.

Siggelkow. N. & Rivkin, J. 2009. Hiding the Evidence of Valid Theories: How Coupled Search Processes Obscure Performance Differences among Organizations. ***Administrative Science Quarterly***, 54: 602-634.

Simon, H. A. 1945. ***Administrative Behavior***. New York: Macmillan Press.

Smith, A. 1776. ***An Inquiry into the Nature and Causes of the Wealth of Nations***. Edinburgh.

Steward, D.V. 1981. ***Systems Analysis and Management: Structure, Strategy and Design***. New York: Petrocelli Books.

Szulanski, G. (1996), Exploring Internal Stickiness: Impediments to the Transfer of Best Practice Within the Firm**,** ***Strategic Management Journal***, 17: 27-43.

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

Turner, B.A., 1976. The organizational and interorganizational development of disasters. ***Administrative Science Quarterly***, 21, p.20.

Tushman, M.L., & Nadler, D.A. 1978. Information Processing as an Integrating Concept in Organizational Design. ***Academy of Management Review***, 3(3): 613-624.

Udell, J.G. 1967. An Empirical test of Hypotheses Relating to Span of Control. ***Administrative Science Quarterly***: 420-439.

Van de Ven, A., Delbeq, A., & Koenig Jr., R. 1976. Determinants of Coordination Modes within Organizations. ***American Sociological Review***, 41(2): 322-338.

Von Hippel, E. 1990. Task Partitioning: An Innovation Process Variable. ***Research Policy***, 19: 407-418.

Von Neumann, J. & Morgenstern, O. 1944 ***Theory of Games and Economic Behavior***. Princeton University Press.

Weber, R. 2004. ***Organizational Coordination: A Game-Theoretic View***. Working Paper, Carnegie Mellon University.

Weick, K. 1993. The Collapse of Sensemaking in Organizations: The Mann Gulch Disaster. ***Administrative Science Quarterly,*** 38(4): 628-652.

Williamson, O.E. 1975. ***Markets and hierarchies: Analysis and antitrust implications.*** New York: Free Press.

Woodward, J. 1965. ***Industrial Organization: Theory and Practice.*** Oxford, UK: Oxford University Press.

Zenger, T.R. & Hesterly, W.S. 1997. The Disaggregation of Corporations: Selective intervention, high-powered incentives, and molecular units. ***Organization Science***, 8: 209-222.

FIGURE 1

Architectural knowledge, Predictive Knowledge and Integration