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# Toward Simulation Models of Knowledge-Intensive Work Processes

By

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# Toward Simulation Models of Knowledge-Intensive Work Processes

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## ABSTRACT

As organizations attempt to do more, faster, with less, they run into information processing bottlenecks. Over the past decade, the Virtual Design Team (VDT) research group at Stanford has operationalized and extended Galbraith's information processing theory in the form of a modeling and simulation language and software tool. For the kinds of fast track, but relatively routine, projects studied by the VDT group to date, sharing of information is frequently the bottleneck to successful project completion. For many kinds of less routine work, however, knowledge sharing among specialists with very different levels of skills and experience is critical to achieving organizational goals, and the flow and processing of knowledge is at least as important to organizational performance as the complementary flow and processing of information. However, the VDT research methods and tools have not been developed to address the unique nature of knowledge and its flow through the organization. This collaborative research builds upon the VDT research stream to incorporate emerging work on the phenomenology of knowledge flow. Defining important dimensions of knowledge flows and investigating the micro-behaviors of agents dealing with knowledge flows that differ along these dimensions, the micro-behaviors of agents performing knowledge work are conceptualized for later embedded as additional micro-behaviors in VDT computational agents. Through new knowledge generated and computational tools to enact such knowledge, this research has the potential to make contributions both to both science and technology.

**Keywords**. Agent-based simulation, information processing, knowledge flow, knowledge management, organization theory.

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## Introduction

The goal of this research is to develop and validate general computational models of organizations that perform knowledge-intensive work activities. To that end, we work toward development and testing of theories that describe the behavior of participants in knowledge-intensive organizations as they work on activities, communicate with one another, share knowledge and manage exceptions. Our approach is to extend previous modeling and simulation research that focused on routine work and the flow and processing of *information* through the enterprise to model and simulate less routine work and the complementary flow and processing of *knowledge*.

Previous simulation research has modeled project-based organizations performing well understood, routine work (Christensen, Christiansen, et. al., 1996; Jin and Levitt, 1996; Jin, Levitt, et. al., 1995a; Kunz, Levitt, et. al., 1998; Levitt, Cohen, et. al., 1994). In modeling these organizations, researchers could assume that work-process activities had a predictable scope, duration and characteristics; exceptions to activities simply added work to pre-defined activities, and thus could be represented uniformly across activities; and the work process and assignments of tasks to members of the organization remained unchanged over the duration of the project. For example, a design-build contractor has an organization to design a well defined building, can pre-specify the design and construction tasks to be completed, and can assign those tasks to organizational members. If an exception occurs, it can be viewed as adding additional work to a pre-defined activity and affect neither the pre-specified work process nor the relationships among activities and organizational members.

Alternatively, for many kinds of less routine work (e.g., in services, health care), more energy is devoted to managing exceptions than to performing the routine work, and exceptions in such organizations often change the work process or the organization in significant ways. They may require re-assignment of organization members to new activities, require the addition of new activities, or streamline the work process by eliminating an existing activity. For example, a service clerk may require a supervisor to assist in a complex transaction that extends beyond her usual duties; a patient may be hospitalized unexpectedly after a treatment, or his care referred to a specialist; the repair of an airplane engine may take less time than anticipated, because unnecessary steps are eliminated as more information about the problem is obtained. Current research (Levitt et al, 2001; Cheng and Levitt, 2001) is extending the state of the art in modeling and simulation to address less routine work processes along these lines.

However, even this extended version of VDT has difficulty simulating the kind of knowledge-intensive work that is becoming increasingly important in the modern enterprise. Where teams of knowledge specialists from different disciplines are required to perform non-routine work, the flow and processing of knowledge becomes at least as important as the flow and processing of information, and many of the work activities themselves are often not predictable (Allen & Hauptmann, 1990). For example, the design of an unprecedented commercial building (e.g., in terms of size, architecture, construction materials) may (or may not) require selected aerodynamicists, seismologists, lawyers, financial analysts, and environmental groups to work integrally with “routine” building-design specialties such as structures, architecture, materials, and construction planning; here, much of the design work itself revolves around sharing diverse specialists’ knowledge, and the exact network of activities cannot be pre-specified in detail. Other examples include teams of geneticists, microbiologists, immunologists, physicians, patent attorneys, and clinical-trials planners involved with the development of new drugs, or groups of politicians, intelligence analysts, tacticians, logisticians, ambassadors, foreign ministers, public-affairs and medical-relief personnel required to plan unprecedented military operations in other nations. Current and emerging simulation models and tools are inadequate for such knowledge-intensive work processes.

In this research, we make distinctions between the concepts *data, information* and *knowledge* as follows. Data describe exogenous, static or dynamic, values of variables relevant to some decision process (e.g., weights, strength properties, prices of raw materials, airline schedules). Information is selected data in a specific context (e.g., which raw materials will be used, the sizes of engineered components, selected paint colors for a specific building; or the requested or confirmed flight and seat numbers for a specific itinerary). Knowledge supports direct action (e.g., correct decisions, appropriate behaviors) and is applied to data to create information (e.g., engineering knowledge is applied to raw materials data to select appropriate construction materials and optimally size components for a given purpose in a specific building; travel planning knowledge is used to select flights and seats to fit a particular traveler's idiosyncrasies).

Computational Organization Theory has examined the work processes and information flows associated with project- or task-based organizations (Carley and Prietula, 1994; Levitt, Cohen, et. al., 1994), and current research is effectively examining the exception-based work and information flows in flexible service organizations (Levitt et al, 2001; Cheng and Levitt, 2001). However, there is little understanding of how to represent and simulate knowledge-intensive work or the flow and processing of knowledge that drives it parsimoniously. Our research seeks to extend the understanding of knowledge flow through new theories capable of modeling these processes.

The fast emerging knowledge economy provides strong impetus for enhanced understanding of how to represent and simulate knowledge-flow processes in modern enterprises, as knowledge-intensive work now represents the principal means of attaining competitive advantage across most industries and economic sectors (Drucker, 1995). *Knowledge capital* is commonly discussed as a factor of no less importance than the traditional economic inputs of labor and finance (Teece, 1998), and many product and service firms now depend upon knowledge-work processes to compete through innovation more than production and service (McCartney 1998). Brown and Duguid (1998, p. 90) add, "organizational knowledge provides synergistic advantage not replicable in the marketplace." In order to diagnose knowledge-processing bottlenecks and design robust organizations to perform knowledge-intensive work, we need new theory and tools for understanding knowledge flows.

## Research Goals and Questions

The Investigators' long-term research goal is to develop new language, theories and tools that will allow managers in a wide range of organizations to design their work processes and organizations in the same way engineers now design bridges, airplanes and semiconductors—by modeling and then simulating the performance of mathematical and computational "virtual prototypes." This paper described our current effort to extend the Virtual Design Team (Jin and Levitt, 1996; Jin, Levitt, et. al., 1993; Levitt, Cohen, et. al., 1994) language, theory and modeling tools previously developed by the investigators for processes associated with work flows. These extensions will allow researchers and managers to model and simulate a wide range of knowledge-intensive work processes. We will generalize and validate the extended modeling and simulation framework on a set of organizations in a fast paced technology firm and a military organization.

Specific research questions we plan to address include:

- What language, theory and tools are required to describe performance variations of organizations and processes involved with complex, knowledge-intensive work? Based on a workshop that the investigators held to explore this question, we are confident that concurrent development of theory and tools in these two domains will allow us to identify significant commonalties between the work processes and knowledge flows of the two domains, and thereby generalize our results.
- To what extent is there validity to the language, theory and tools to describe performance variations of organizations and processes involved with complex, knowledge-intensive work? To determine the extent to which our models and analysis are descriptive of knowledge work in practice, we have outlined an evaluation trajectory that will go a long way toward building a case for the validity of our approach.

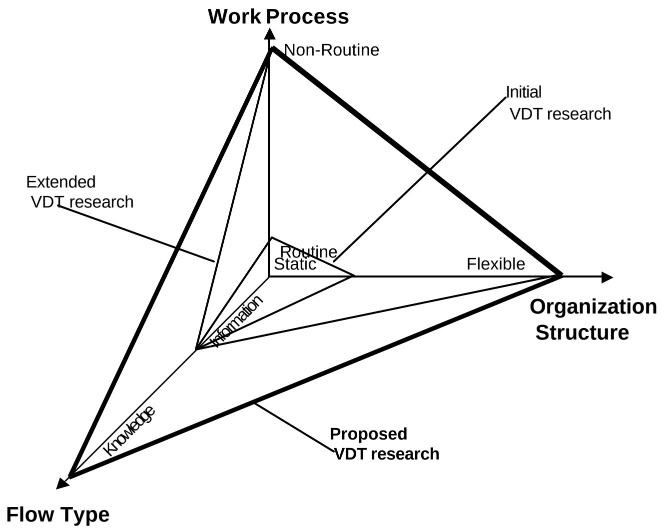

**Figure 1 Contributions of Proposed Work**. This diagram illustrates the relationship of our proposed work to prior and current research. We will develop representations of processes associated with the flow of knowledge in non-routine work processes performed in flexible organizational structures.

## Expected Significance

This research has the potential to make significant contributions both to science and technology. The contribution to science is to extend the Galbraith/VDT computational information-processing framework to embrace knowledge processing, thus extending its fidelity and range of applicability for many kinds of non-routine, knowledge-intensive work. At the same time, once validated, the more complex agent-based simulation framework can be productized as a diagnostic software tool and applied to designing organizations for a broad range of knowledge-intensive, real-world projects for which the commercial derivatives of VDT are not currently applicable.

The VDT Computational Organizational framework, based on Galbraith's information-processing abstractions (1974; 1977), has proven to be a very powerful approach for simulation of relatively routine—albeit unusually fast paced—design and product development tasks (Jin, Levitt, et. al., 1993; Jin, Levitt, et. al., 1995b), and it is currently being extended to model less routine work associated with service and maintenance tasks. If VDT can be augmented to model knowledge-intensive work, the same kind of organization design theory and tools can be extended to address the complex class of work now driving most competitive advantage in the modern economy.

# Background

The investigators have been working since the early 1980s to formalize language, theory and tools for work-process modeling. They collaborated with various colleagues on the "Platform" project, a knowledge-based system that reasoned about project activities and risk factors that could impact those activities, and then generated intelligent forecasts about remaining project activities (Levitt and Kunz, 1985; Levitt and Kunz, 1987). Subsequently, they developed the Object-Action-Resource Planner (OARPLAN) to automate the generation of assembly plans for construction projects by reasoning about CAD representations of the facility to be built (Darwiche, Levitt, et. al., 1989). They then extended OARPLAN to automate the pro-active planning of just-in-time maintenance activities in the IRTMM project (Kunz, Yan, et. al., 1996a). The Knowledge-based Organizational Process Redesign (KOPeR) system followed (Nissen, 1996a; b; 1998), which employed graph-based process measurements and heuristic classification to automatically diagnose work-process pathologies and guide enterprise designs.

Recent research includes work to extend the VDT to represent and simulate dynamic work processes and flexible organizational structures associated with service work (Levitt et al, 2001; Cheng and Levitt, 2001) and a project to understand the phenomenology of knowledge flow in the very large enterprise (Nissen et al., 2000; Nissen, 2001a; b). This line of research led to the discovery of parsimonious and powerful approaches to represent work processes symbolically, and a rich model of enterprise knowledge flow was conceptualized to represent the complementary knowledge processes. These insights were critical to the success of our later research on organization design tools and are leveraged in the proposed research project. Here we summarize key elements of VDT research and the related literature.

## VDT Research

In this section, we briefly summarize highlights of the VDT research stream. This begins with foundational work from the 1980s and continues to current work.

### *Foundational Work: 1980s*

Starting in the late 1980s, the PIs launched the "Virtual Design Team" (VDT) research project to develop language, theory and tools that could advance the state of the art of organizational engineering toward a formal organizational design process. Organizations have been usefully categorized in terms of the extent to which their goals and means are understood and agreed upon (Thompson, 1967). We recognized that the language, theory and tools for organizational designs were far less mature than those for the physics that underlie much of modern engineering were. We thus chose to focus initially on the part of the organizational design space that we felt was best understood and defined—organizations engaged in routine project-oriented tasks. For such organizations, goals are clear and relatively congruent, and the technology of work is formalized and well understood (Figure 1). In four previous NSF projects, we formalized and extended the organizational information-processing language and theory applicable to this class of organizations and built modeling and analysis tools incorporating our extended micro-contingency language and theory.

### *The Virtual Design Team: 1992-1995*

Under an initial NSF grant, the VDT research group built a unified theory and computer model of fast paced but routine product-development projects, which relates product requirements, time-to-market objectives, process quality and organizational resources needed to achieve them. Implemented in a computer simulation, the VDT model describes and predicts useful and measurable aspects of project schedule, quality and cost. Unlike PERT/CPM project scheduling tools, which ignore coordination and rework, VDT generates reliable predictions of participant backlogs arising from extra coordination and rework in highly concurrent product development efforts, along with the resulting delays and "quality meltdowns" that will occur if the organization configuration is left unchanged.

The "routineness" of the work processes in the routine engineering domain allowed us to model work processes as sets of relatively abstract, sequentially and reciprocally interdependent (Thompson, 1967) information-processing activities. VDT organizational actors are relatively simple information processors and communicators with finite or “boundedly rational” capacity (March and Simon, 1958); and organizations serve as “exception handling machines” in the spirit of Galbraith’s information-processing view of organizations (Galbraith, 1973; Galbraith, 1974). These abstractions allowed rapid progress of the VDT research but limited its applicability to a relatively small fraction of all organizations. The VDT language, theory and tools (Kunz, Christiansen, et. al., 1997; Levitt, Cohen, et. al., 1994; Thomsen, Kwon, et. al., 1997) are now being used for teaching and research on project-oriented organizations in more than a dozen US and foreign universities. The VDT framework and tools have been commercialized and currently support the design of project-oriented work processes and organizations in a number of major companies and government agencies, and is used to teach organization design in more than 20 Universities, worldwide.

### *Computational Enterprise Modeling: 1994-1997*

Our second grant from the “Toward Quality Organizations” (TQO) program of NSF allowed us to extend the VDT framework with ideas from economic “agency” theory (Eisenhardt, 1989) and social psychology (Amason, 1996; Jehn, 1995; Pelled, 1996; Watson, Kumar, et. al., 1993; Weick, 1979) to model and simulate the behavior of project participants with incongruent goals. The goal of this TQO project was to extend the VDT framework to model goal incongruency and its effect on project teams, and to apply the extended VDT framework to projects in our partner, Lockheed Martin’s, aerospace domain. The TQO project links Total Quality Management (TQM) theory with theory and practice of computational organizational modeling and simulation.

The first project we modeled was the Lockheed Martin Launch Vehicle (LMLV), a commercial version of Lockheed’s Trident Missile, now implemented substantially faster in the competitive global satellite launch market. For this project, VDT clearly predicted the risk of backlog in the external team developing an outsourced component of the LMLV avionics package, as well as a serious quality problem and resulting delays. Because of lack of sufficient prior experience with the modeling methodology, neither the investigators nor the project management intervened based on this prediction. The backlog and its impacts later materialized exactly when and where predicted and had to be managed with a subsequent high impact on project cost and schedule.

With newly developed confidence, we prospectively applied the simulation model early in the design of a second Lockheed-Martin project: development, procurement and testing of a critical component of a Lockheed Martin satellite. Considering the simulation model predictions, the cooperating project manager intervened in the engineering process to reduce some of the organizational risks that we predicted might adversely impact project performance. In subsequent project observations, the potential problems did not appear. We introduced mechanisms of goal incongruency into the VDT model, collected data from the Lockheed project regarding participant goals, and compared observations with simulated predictions. We learned that the goal incongruency model usefully predicts important effects on project performance and quality of changing levels of goal incongruency among project participants.

This grant resulted in an extended organizational design language, theory and tool set, and it culminated in a well attended workshop during July of 1997 for academics interested in using VDT in their teaching and research. We concluded that the Virtual Design Team model can effectively describe fast paced project plans and supporting organizations with varying degrees of goal alignment, and it can predict project schedule, process quality and cost risks. Further, we concluded that VDT could enable managers to identify, choose, carry out and manage interventions to reduce predicted risks.

### *Simulation Models of Dynamic Work Processes and Organizations: 1999-2002*

To model the impact of exceptions in routine engineering work, VDT simply added work volume to predefined activities in a fixed organization structure. This abstraction has proven very successful for modeling product development tasks, but it breaks down for less routine service tasks. To address this shortcoming, multiple kinds of stochastic exceptions must dynamically modify both the work process and performing organization. This extended IP framework should be able to model and simulate the inherent uncertainty of service work and the more dynamic organizational structures of service organizations. Douglas Fridsma (now on the faculty at University of Pittsburgh Medical School) developed the prototype of the service extension to VDT and has validated it on health care delivery work processes and organizations in a bone marrow transplant clinic and an internal medicine outpatient clinic (Thomsen et al, 1999). Carol Cheng has extended Fridsma's prototype to capture the effect of several different work contexts (e.g., time of day, day of week, own backlog, colleagues' backlog) on the micro-behavior of personnel involved in health care delivery (Cheng and Levitt, 2001). Carol is about to commence validation of her extensions within several clinical settings at the Palo Alto VA Hospital.

### *Co-Evolution of Knowledge Networks and Twenty-First Century Organizational Forms: current work*

This ongoing research aims to identify the factors that lead to the formation, maintenance and dissolution of dynamically linked knowledge networks. Two core research questions will be addressed: How do diverse knowledge networks co-evolve over time and at multiple levels? How do the centrality, density, diffusion and other properties of knowledge networks at each level affect task performance by individuals, groups and organizations? The PIs adopted a broad, generic approach to understanding the co-evolution of knowledge networks. Public Goods theories describing the emergence of communal and connective knowledge resources have been integrated with ideas from transactive memory, and with information processing views of organizational work processes. Researchers at CMU and Stanford have begun to embody these new theoretic syntheses into computational models that can be used to predict the performance of organizations engaged in sharing and integrating knowledge. Researchers at U. of Illinois have deployed software for visualizing knowledge networks and for modeling networks of agents interacting. This research has supported two PhD students at Stanford. Monique Lambert and Ray Buettner are attempting to develop and test computational models based on VDT to model and simulate team members using connective knowledge-sharing networks of colleagues and communal knowledge repositories, respectively, to address exceptions, rather than simply resolving exceptions by passing them up the hierarchy, as in VDT. These provide additional planks in the conceptual and software platform of VDT upon which the current research will be based.

## Relationship to Current State of Knowledge in Related Fields

Knowledge is power. But knowledge is not evenly distributed through the enterprise, and the performance of knowledge-intensive enterprises (e.g., involved in business, engineering, healthcare, military warfare, service delivery) is particularly dependent upon knowledge flow. But before one can expect to design knowledge-intensive work processes in the enterprise, one must first understand the phenomenon of knowledge flow itself, along with key contextual factors that may affect this phenomenon. This study builds directly on basic science to understand the phenomenology of knowledge flow (ONR Young Investigator Program: N0001401WR20304), which resulted in the conceptualization of a four-dimensional model to represent and classify diverse patterns of knowledge flow in the enterprise. This model elucidated sharp distinctions between knowledge and its information/data counterparts, particularly in terms of the associated work activities. Through this research, it became clear that the processes responsible for driving the flow and processing of knowledge through an enterprise are also distinct from the complementary processes associated with the flow and processing of information and work through an organization. Thus, to model and simulate knowledge-intensive work, an explicit representation of knowledge-flow processes is required to augment the complementary representations used to model the flow and processing of information and work in the organization. Here we summarize key literature related to the present research.

### *Computational Organization Theory*

Two recent books describe the “growing awareness among organizational theorists that people, tasks and the socio-structural situations defining people’s interaction networks matter” (Carley and Prietula, 1994; Prietula, Carley, et. al., 1998). The books describe work of a number of investigators that combine multiple perspectives (e.g., agents, tasks, organizational networks) and computational formalisms to describe the attributes and behaviors of their models. Our research lies in this emerging tradition. Burton and Obel’s Organizational Consultant (Burton and Obel, 1995a) can model a variety of organizations at the macro-level and can assess the goodness of fit between their situation and structure. However, their approach considers organizations at a macro level and cannot be used to consider the impact of individual activities and organizational participants.

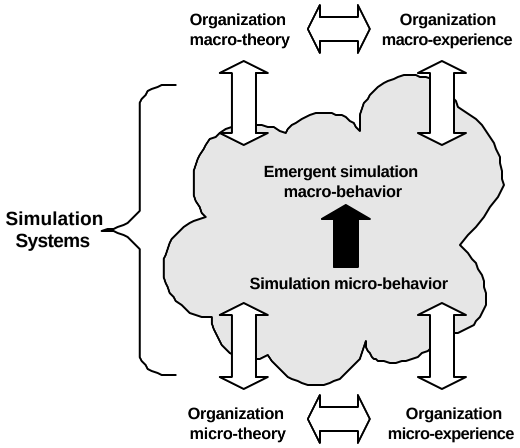

**Figure 2 Simulation systems bridge the gap between theory and experience at a micro and macro level.** Before simulation tools, it was difficult to relate micro and macro organization theories or experiences rigorously. Simulation of micro-behaviors and their interaction generates macro-predictions that can be tested against both predictions of macro theory and macro organization experience.

In traditional organizational research, theories describing the aggregate behavior of organizations (i.e., macro-theories) are compared to observations of organizational behavior (i.e., macro-experience). Likewise, theories of agent interactions (i.e., micro-theories) are compared to the experience of agents in the organization (i.e., micro-experience). Because of the complexity of both organization theory and observation, relating macro-theories and macro-experiences to micro-theories and micro-experiences is difficult.

Simulation systems used in computational organization theory are intermediate representations that relate micro-theories and micro-behaviors to emergent macro-theories and macro-behaviors. Within computational organization theory, there is a spectrum of different simulation and research emphases. Certain computational models emphasize deliberately simplified “toy” problems, or larger scale, idealized organizations—called “Intellective simulations” (Burton & Obel 1995b)—that illustrate conceptual or theoretic extensions to organization theory (Carley, 1997; Carley and Svoboda, 1996; Carley and Zhiang, 1997; Masuch, 1985). Other models emphasize emulation simulation models that can give practitioners useful advice in real world organizations (Christensen, Christiansen, et. al., 1996; Cyert and March, 1963; Jin, Levitt, et. al., 1993; Kunz, Yan, et. al., 1996a; Thomsen and Kwon, 1996; Thomsen, Levitt, et. al., 1998b). Both types of simulation models sit between the micro-behavioral theory they encode and the meso- or macro-organizational real-world observations they assist us in understanding. The relationships among theory, simulation models and organization experience are shown in Figure 2.

The Computational Organization Theory literature includes models of decision making and communication in education (Cohen, 1992), design, (Jin and Levitt, 1996; Levitt, Cohen, et. al., 1994), clerical work (Masuch, 1985; Masuch and LaPotin, 1989), radar interpretation (Carley and Zhiang, 1995; Carley and Zhiang, 1997), and other domains. Current work is applying COT models to dynamic service and maintenance tasks and the less well structured organizations that perform them (Levitt et al, 2001). There is little research to date that addresses the flow and processing of knowledge required for knowledge-intensive work.

## *Rationale for Using Information Processing as the Modeling Framework*

The information-processing (IP) perspective on organizations, first suggested by March and Simon (1958) and later refined by Galbraith (1973; 1995), models organizations as “information-processing and communication systems” whose capacity is limited by the “bounded rationality” of their participants. High task and environmental uncertainty relative to workers’ skill levels lead to “exceptions”—non-routine situations for which the responsible participant lacks some of the necessary information. In turn, interdependence between the subgoals of participants creates the need to communicate with supervisors or peers about exceptions using communication channels (e.g., supervisory or peer-to-peer relationships, supported by communication technologies, including face-to-face contact). The knowledge and experience of its participants, and the way in which they are organized into a particular structural configuration, determine each organization's capacity to process this information. An organization's information-processing capacity should be well matched to its demand for an optimal organization design (Tushman and Nadler, 1978).

This IP perspective underpins a relatively simple but powerful theory that can provide good first-order predictions of an organization's information-handling capacity, with respect to the demand for participants to process exceptions and coordinate activities. In this respect, the IP perspective is analogous to Newton's Laws of Motion in physics. After subsequent research by Newton, Einstein and others, we know that phenomena like friction and quantum mechanic effects also influence the motion of particles and must be accounted for in some situations. Nonetheless, the original Newtonian Laws of Motion are simple, and they provide valuable and accurate-enough first-order predictions for many situations. Similarly, the IP framework can be viewed as a "first order information physics theory" to predict an organization's capacity to process decision making and communication workload.

Since the initial research by Galbraith and others, there has been significant progress both in applying IP theory and in developing other valuable and complementary perspectives on organizations. For example, OrgCon (Burton and Obel, 1995a; 1998) operates at the macro-level, and its macro-contingency rules are able to encompass many kinds of organizations, with more or less clear goals, engaged in more or less routine work and in more or less turbulent environments. VDT's work processes are quite detailed, so the coverage of VDT was limited initially to project organizations whose goals are clear and whose technologies are well understood. An information-processing view of organization, then, can be operational at both the macro and micro levels of the organization.

Other theories such as institutional theory (DiMaggio and Powell, 1983), population ecology (Hannan and Freeman, 1977), and agency theory (Eisenhardt, 1989) have developed since Galbraith's early work. By 1998, it had been clearly demonstrated and reported that "organizational chemistry" perspectives such goal incongruency (Eisenhardt 1989), institutionally driven imitative behaviors (DiMaggio and Powell, 1983), and "organizational quantum mechanics" such as structuration theory (Giddens, 1984; Sewell, 1992) can significantly extend and refine IP predictions about the effectiveness and efficiency of organizations. We have found the IP framework to be a good starting point and flexible enough to incorporate aspects of some of these new theories (Thomsen, 1998; Thomsen, Levitt, et. al., 1998b).

Managing information has become an increasingly important part of the modern organization. In service industries in particular, the role of information in the efficient operation of the organization has become ever more important, as services now account for nearly 80% of all employment across industries (CEITPSA 1994). Further, emerging research on knowledge management (Nissen et al., 2000; Nissen 2001a; b) suggests that the flow and processing of information is integral to—albeit distinct from—the flow and processing of knowledge, the latter of which is central to the kinds of knowledge-intensive work that increasingly drive competitive advantage in the modern economy. Thus, we assert that the design of modern organizations can fruitfully be considered using an information-processing view—once augmented to incorporate knowledge flow and processing: It provides a framework that can be used at macro- and micro-levels of analysis; it is flexible enough to be extended by other theories; and given the integral relationship between knowledge and information flows and processing, it appears to be highly promising to modern knowledge-intensive organizations.

# Research Approach

To achieve the goals outlined above, our research approach involves X steps: 1) address requirements for modeling knowledge-intensive processes; 2) develop representations of knowledge flow; 3) understand how knowledge-intensive process design can be made systematic; and 4) implement a scheme for computer-based modeling of knowledge-intensive processes.

## *Requirements for Modeling Knowledge-Intensive Processes*

Moving from processes associated with the flow of information to those that drive the flow of knowledge requires additional modeling effort. For most processes (e.g., routine and less routine, product- and service-oriented), sharing of information is frequently the bottleneck to successful project completion. Knowledge sharing within disciplines is less critical for these kinds of projects, due to the routineness (e.g., with respect to the actors' skill levels) of the technical work within each discipline. For many kinds of less routine work, however, knowledge sharing among specialists with very different levels of skills and experience is critical to achieving organizational goals, and the flow and processing of knowledge is at least as important to organizational performance as the complementary flow and processing of information. This may be the critical bottleneck for knowledge-intensive work processes, as boundedly rational actors contend with the requirement to share large amounts of information and knowledge simultaneously, both within and across disciplines. To simulate the way an organization would perform these tasks within a particular setting, we must also consider the conditional aspects of these tasks and identify the patterns of diverse knowledge flows for process quality evaluation metrics.

## *Representations of Knowledge Flow*

We identify high-tech, new-product design and military warfare as two good examples of knowledge-intensive work. In the former case, knowledge workers with different backgrounds and areas of expertise (e.g., business, engineering, law, marketing, production) must quickly form an effective team, acquire any critical skills that are missing, collaborate effectively and create an unprecedented design. Similarly in the latter case, military officers and enlisted personnel with different backgrounds and areas of expertise (e.g., air defense, intelligence, navigation, combat tactics) must quickly accomplish tasks comparable to those above (e.g., team formation, critical skills acquisition, collaboration) to defeat a military adversary in battle. In both cases, all of the requisite knowledge must come together and be integrated before the knowledge-intensive work can be completed. If even a single element of knowledge (e.g., specific education, experience, patent, skill) is missing, the project—whether it is new-product design, military warfare, software development or some other knowledge-intensive task—is destined to fail. All requisite knowledge must complete its flow through the enterprise prior to completion of the knowledge-intensive process, and given the long lead times required for certain kinds of knowledge (e.g., tacit, embodied, intuitive, experiential) to flow, this represents a critical process element.

Through prior research on the phenomenology of knowledge flow (Nissen, 2001a; b; 2002), four dimensions from the literature were identified and integrated to conceptualize the flow of knowledge: 1) *explicitness* (e.g., degree to which knowledge can be articulated), 2) *organizational reach* (e.g., individual, group, department), 3) *life cycle* (e.g., creation, distribution, dissemination), and 4) *flow time* (e.g., minutes, days, years). These dimensions appear to be robust for modeling a diversity of knowledge-intensive processes, and they are envisioned to support the identification, classification and visualization of many potentially important knowledge-flow patterns (e.g., critical paths, bottlenecks, sources, sinks, cycles) in the enterprise. The improved understanding available through models of the processes that drive enterprise knowledge flows can lead to new diagnostics of process pathologies and novel designs for business processes that are not apparent through models, tools and techniques that are currently available.

## *Systematic Knowledge-Intensive Process Design*

There is still very little known about how best to design and implement knowledge-intensive processes in organizations. Knowledge is integrally related to, but distinct from, information and data (Davenport et al., 1998; Nonaka, 1994; Teece, 1998; von Krough et al., 2000), but most information technology, for instance, employed to enable and support knowledge work targets data and information, as opposed to knowledge itself (Ruggles, 1997). The flow of knowledge in the enterprise is complementary to but distinct from the flow of information and work (Nissen et al., 2000; Nissen, 2002), but models, techniques and tools associated with business process re-engineering (Davenport, 1993; Hammer, 1990; Harrington, 1991; El Sawy, 2001; Koch and Murphy 2001) focus exclusively on the flow of information and work, not the flow of knowledge. Nissen et al. (2000) develop a systematic, four-step method to integrate knowledge-process design with information-system design in organizations, but this method is not presently embedded in work process simulation models.

With the identification of knowledge-flow patterns and corresponding development of metrics and heuristics to diagnose process pathologies, the design of knowledge-intensive organizations can be made more systematic, thus obviating the need for trial and error and other, asystematic approaches (e.g., pure imitation) employed today. By focusing directly on the processes that drive knowledge flow through the enterprise, this systematic design can be applied directly to the kinds of knowledge-intensive processes that are proving so difficult to develop, adapt and refine (Davenport 1995).

### *Computer-based Modeling of Knowledge-Intensive Organizations*

Knowledge-intensive activities involve extensive information processing and communication, so an information-processing view is a logical abstraction within which to frame our simulation and a representation (Section 0). We have found structural contingency theory and the literature that has developed from it on organizational design as one of the most promising theoretical approaches to understanding organizational performance (Pfeffer, 1996), and organization theorists have used the information-processing view of organizations in a broad range of domains (Galbraith, 1973; Galbraith, 1974; March and Simon, 1958; Thompson, 1967; Tushman and Nadler, 1978). In this view, an organization consists of an information-processing and communication structure, designed to achieve a specific set of goals, and comprised of limited-capacity (i.e., “boundedly rational”) individuals. A knowledge-intensive organization could be modeled as an information-processing and decision-making machine, but this will require augmentation of the information-processing model to integrate the flow and processing of knowledge as well.

# Research Design

It is our goal to create a virtual prototyping environment for designing work processes and organizations for knowledge-intensive work. This section outlines the research steps needed to develop a new *representational language*, *theory* and *set of tools* to investigate knowledge-flow processes and contingent behavior to support this design process.

## Extend Representation Language

This project builds upon considerable prior research, which has been undertaken by several researchers over many years. In extending the representation language, three primary tasks are required: 1) dimensionalize knowledge flow; 2) adapt VDT representation; and 3) model knowledge-flow mechanics. In the following sections, we describe these knowledge-flow extensions to VDT that we believe will allow parsimonious representation of knowledge-intensive organizations using an information-processing framework.

### *Dimensionalize Knowledge Flow*

The literature on organizational learning provides a high level metaphor that is useful for conceptualizing knowledge flow in engineering terms. When knowledge flow is viewed in the context of organizational learning, such learning can be conceptualized as the *derivative* of an organization’s knowledge with respect to time; that is, knowledge flow represents the time-based rate of change in an organization’s knowledge stock. Hence, we can begin to extend the VDT representational language by considering the flow of knowledge in terms of differential or difference equations, in which the quantity *knowledge* varies as a function of time. But to identify, discern and model various knowledge-flow patterns expected to be important in practicing knowledge-intensive organizations, further dimensionality for our knowledge-flow model is required.

Recent research has conceptualized a four-dimensional model of knowledge flow. Each of the four dimensions is drawn from the literature and offers good potential to describe the flow of knowledge in practicing organizations. The first two dimensions, *explicitness* and *reach*, were first proposed by Nonaka (1994) in the context of organizational learning. The *explicitness* dimension depicts a binary contrast between explicit and tacit knowledge. Explicit knowledge can be formalized through artifacts such as books, letters, manuals, standard operating procedures and instructions, whereas tacit knowledge (Polanyi, 1967) pertains more to understanding and expertise contained within the minds of people and is much more difficult to share. Instead of a simple binary contrast as conceptualized by Nonaka, however, we propose that knowledge fills a continuum along the dimension characterized by tacit and explicit endpoints. Continuizing this dimension will enable us to trace knowledge as it flows through a continuous *range* of explicitness. In terms of operationalizing this dimension, which is required to represent knowledge flows that occur in practice, we noted above that knowledge enables direct *action* (e.g., correct decisions, appropriate behaviors). The action-enabling property of knowledge allows us to draw from research on learning and pedagogy (Bloom, 1956)—where the explicitness of knowledge to be learned is mapped to a range of cognitive actions (e.g., memorization, comprehension, application) enabled by such learning—to guide this operationalization.

The *reach* dimension depicts knowledge that is shared by individuals with others in small work groups or larger aggregations of people across the organization. Although this aggregation of organizational units appears arbitrary, in the enterprise context, it could clearly apply to small teams, work groups, formal departments, divisions, business units, firms and even business alliances or networks. We also theorize the dimension *reach* in terms of a continuum. In terms of operationalization, we will examine this construct in terms of the number of people associated with a particular knowledge flow (Nissen, 2001a) to guide this operationalization.

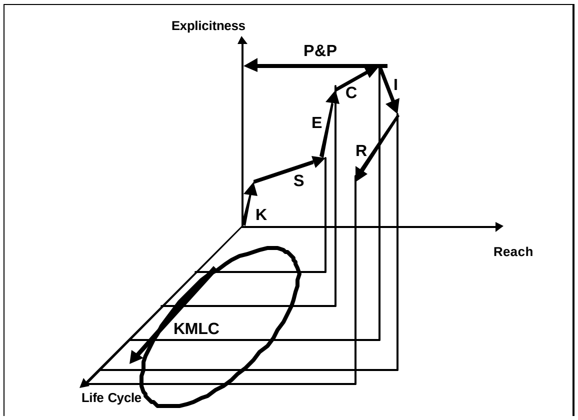

**Figure 3 Knowledge-Flow Vectors**. Using three dimensions, one can readily plot and discern a variety of diverse knowledge-flow patterns.

The third dimension, *life cycle*, was developed empirically by Nissen et al. (2000) through examination of many different life-cycle models developed to describe the flow of knowledge in an enterprise. Integrating their survey of the literature (e.g., Despres and Chauvel 1999, Gartner Group 1999, Davenport and Prusak 1998, Nissen 1999), they synthesize an amalgamated knowledge life cycle model comprised of six phases: 1) create, 2) organize, 3) formalize, 4) distribute, 5) apply, and 6) evolve. Briefly, the "create" phase begins the life cycle, as new knowledge is generated by an enterprise. The second phase pertains to the organization, mapping or bundling of knowledge. Phase 3 addresses mechanisms for making knowledge formal or explicit, and the fourth phase concerns the ability to share or distribute knowledge through the enterprise. Knowledge application for problem solving or decision making in the organization constitutes Phase 5, and a sixth phase is included to cover knowledge evolution, which reflects organizational learning through time. We will also strive to continuize the ordinal scale for this dimension.

The fourth dimension, *time,* is inextricably tied to dynamic systems and processes. In the case of modeling knowledge-intensive organizational work, we are most interested in the flow time associated with knowledge, for current research (Nissen, 2002) suggests that flow rate is directly related to organizational performance, particularly in situations where knowledge is unevenly distributed and its rapid flow (e.g., via sharing, dissemination) is required for effective performance of knowledge-intensive work. This current research further suggests that different types of knowledge (e.g., with varying degrees of explicitness, different levels of reach, alternative life cycle phases) can flow at dramatically different rates (e.g., hours, months, years) and call for specific, context-dependent organizational designs and technological enablers.

In Figure 3, we note a few, notional, knowledge flows that can be delineated in terms of a vector space representation for illustrating and classifying various dynamic patterns of knowledge as it flows through the enterprise. Because it is difficult to visualize four-dimensional spaces, however, we use only three dimensions at a time in graphical displays. For instance, the simple, linear flow labeled "P&P" depicts the manner in which most enterprises inform and train employees through the use of policies and procedures: explicit documents and guidelines that individuals in the organization are expected to memorize, refer to and observe. This simple flow is delineated as a single vector parallel to the *reach* axis, as highly explicit knowledge flows, from the organizational reach level to specific individuals, during the distribution phase of the life cycle. As another instance, the cyclical flow of knowledge described by the amalgamated knowledge management life cycle model noted above, depicted and labeled as "KMLC" in the figure, reflects a more complex dynamic than its simple, linear counterpart. And as depicted, this latter flow delineates a cycle of knowledge creation, distribution and evolution within a workgroup. Further, Nonaka's (1994) dynamic theory of knowledge flow can also be delineated in this space by the curvilinear vector sequence K-S-E-C-I. Clearly, a great many other flows and patterns can be depicted in this manner, and other vector representations can be developed using *time* explicitly as well. We will employ this vector-space approach to extending the VDT representation language in this project, and we expect the capability for visualizing knowledge-flow patterns to be particularly elucidative and useful for diagnosing work-process pathologies and designing knowledge-intensive organizations.

## *Adapt VDT Representation*

The basic VDT representation is predicated on networks to model the flow and processing of work through an organization, the flow and processing of information in an organization, and the handling of exceptions in the processing of work. This representation has been employed and validated on numerous projects of a relatively routine nature. Current extensions to the VDT language support the representation of less routine work processes and include: representing contingent behavior as decision-branch activities (e.g., building on the work of Gordon 1995, Gordon, Johnson et al. , Tu and Musen 1996, Malone, Crowston et al. 1993, Hahar and Musen 1995, and Levitt and Kunz 1987); representing dynamic plan revision using plan-modification strategies (e.g., by defining four classes of exceptions that capture additional detail about how the exception affects the work: exceptions that *add* activities, *modify* activity characteristics, *re-assign* activities to a new agent in the organization, *delete* activities from the work process, or *substitute* one activity for another); representing dynamic activity assignment (e.g., by "splicing" new activities into the work-process network); representing dynamic priority assignment (e.g., based on factors such as status on the critical path and different estimates of activity risk); and representing controllable and uncontrollable exceptions (e.g., by defining activity-outcome uncertainty factors). In addition, work by Lambert and Buettner on the Stanford PI's current KDI grant is creating capabilities to model the storing and retrieval of knowledge from communal knowledge repositories, and to model team members using their transactive memory (their knowledge about who knows what) to direct new information to the appropriate specialist who can best accumulate it, and to retrieve specialized knowledge that they need from those experts who are most likely to possess it.

This extended VDT representation requires further augmentation to model knowledge flows. Building upon our dimensionalization task above, we will introduce symbolic "difference equations" into the VDT modeling language to represent and reason about time-based changes to stocks of knowledge as the knowledge flows through the organization. The "difference equations" will be based upon the four dimensions from above, as knowledge flows will be represented in a four-dimensional vector space in VDT. Because precise numerical measurements or estimates of such knowledge-flow vectors may be infeasible or impractical to obtain in operational organizations, we will draw from techniques developed through qualitative reasoning (de Kleer and Brown, 1984; Forbus, 1984; Kuipers, 1986) for representational and inferential guidance. This extended representation will also draw from recent theoretical work (Nissen and Espino, 2001; Oxendine and Nissen, 2001) to characterize knowledge-flow processes themselves as work processes and information flows through recursion; that is, in some cases, processes that drive the flow of knowledge through an organization (e.g., training, on-the-job experience, mentorship), termed *vertical processes* for the manner in which diagrams are generally drawn, can themselves be modeled in terms of "normal" work flow and information processing, termed *horizontal processes* for the same reason. If we can identify and take advantage of such recursive relationships, this may prove to be an elegant approach to knowledge-flow representation.

## *Develop Knowledge-Flow Mechanics*

Despite the several models and various theoretical works noted and cited above, upon which we build and from which we draw in the proposed research, little is known about the mechanics of how knowledge flows through the enterprise. Through field research, planned as a multiple case study design (Yin 1994), we will immerse ourselves within the contexts and operations of at least two knowledge-intensive organizations, and using the theoretical concepts and constructs described above (e.g., four-dimensional model, vector-space representation, vertical and horizontal processes), we will directly observe and interpret knowledge-intensive work to develop a model of the mechanics underlying knowledge flow.

The case study design envisions multiple sites to provide for comparison and contrast, and to support generalization. One site will involve naval warships at sea as they participate in military-warfare activities. Warfare has been identified as an extreme knowledge-intensive process (e.g., in terms of the immense organizational size, huge geographical areas of operation, hazardous environment, time-critical operations), and many knowledge flows (e.g., associated with coordination, team formation, training) in less extreme counterpart processes in industry and government may reduce to subsets and specializations of such flows. Additionally, the extreme nature of warfare processes is expected to generalize well to other large enterprises such as telecommunications firms, global manufacturing companies and many governmental agencies. By studying such an extreme case, across multiple levels of analysis (e.g., individuals, work groups, organizations), we expect to encounter a rich and diverse multitude of knowledge flows for understanding and synthesis into a model of knowledge-flow mechanics. The second site remains to be determined, as we plan to conduct the two case studies in series, and we want to obtain and evaluate the results of the first study before selecting a second site to best take advantage of such results. However, a commercial organization involved in new-product development is most likely, as it is also knowledge-intensive in nature, and studying a commercial firm will provide a good contrast to the military organization from above and enhance the generalizability of our results.

The case study will employ multiple data-collection methods (e.g., document review, semi-structured and unstructured interviews, direct observation, informants, artifact use) to enhance construct validity, and a case study database will be maintained to enhance reliability. A case study protocol will also be developed in advance of fieldwork to enhance reliability, and the PI will triangulate across data collected through multiple methods to reduce bias and enhance generalizability. Each case will be analyzed with a single unit of analysis at first (i.e., knowledge flow), but based on prior field research to study the phenomenology of knowledge flow (Nissen 2002), the opportunity to identify and investigate multiple, embedded units of analysis is highly probable. The investigation of multiple cases with multiple units of analysis would classify this as a "Type 4" case study design using Yin's (1994) terminology.

## Build Analysis Tools

We will instrument the simulator to produce a number of measures of organizational performance. Examples of such output measures might include:

- *Response lag time, i.e., use the dynamics inherent in knowledge flows to gauge the knowledge-flow rates in various parts of a particular organization and process;*
- *Response quality, i.e., processing speed and error rates are related to participant skill levels in VDT; thus changes in skill level produced by knowledge flows will translate directly into changes in efficiency and effectiveness outcomes. We will use measures of work-process performance to assess the efficacy of knowledge-intensive processes associated with various designs;*
- *Process resources, i.e., amount of time the activity uses doing planned direct work, time used by coordination and rework, and wait time.*

Each of these and other measures of process quality will be calculated in the aggregate over a number of cases to process (e.g., a month's work of a product-design group or military unit). In addition, we will develop methods to estimate and display these measures dynamically to show how they vary over a simulation horizon.

## Model Validation

Evaluation of complex computational organizational models is an important part of computational organization theory (Baligh, Burton, et. al., 1994; Thomsen, Levitt, et. al., 1998a). Computational models that emulate real-world situations often require a long-term evaluation strategy. Before organization and protocol designers use these models, they must have confidence that these models will provide useful advice. We see the development and evaluation of computational models as a tightly linked, iterative process, and this is reflected in our validation plan.

Because not all simulation models are created for the same purpose, their evaluation should be tailored to reflect their design intention (Burton and Obel, 1995b). Law and Kelton (1991) argue that validation of emulation models is a matter not of "valid" or "invalid," but rather of degree. Building emulation models is an iterative process, with each successive validation experiment adding confidence in the model and its predictions.

We propose a validation trajectory that builds a case for confidence in our theoretic extensions and computational tools, and we describe three components to our validation; (1) evaluation of reasoning; (2) evaluation of reasoning and representation; and (3) evaluation of reasoning, representation and usefulness. Our general evaluation plan is described in Figure 4.

In our evaluation of reasoning, we test the way in which micro-theories (i.e., agent behaviors) are encoded using *"toy" problems*, and use *intellective* experiments to examine how micro-behaviors affect emergent macro-behaviors (i.e., organizational behaviors) for idealized cases. This evaluation will

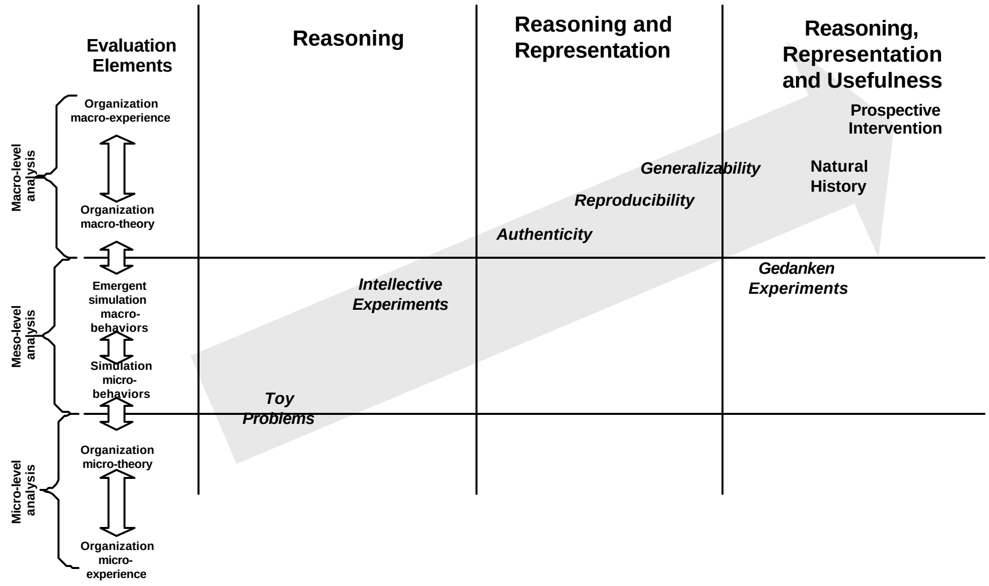

**Figure 4 Evaluation Trajectory of Simulation Systems** *We propose an evaluation plan that builds a case for validation based on a series of experiments aimed at particular aspects of our research. The experiments shown in italics are those that we will complete as part of our proposed work.*

compare the macro-behaviors predicted by theory to the behavior exhibited by the simulation and test how well we have encoded theory within our simulation framework.

Our evaluation of representation and reasoning consists of three parts: authenticity, reproducibility and generalizability. Evaluation of authenticity will use experts to examine how well we can represent and emulate a real organization and provide an assessment of face validity. Reproducibility has to do with the consistency of simulation models of a given work process and organization produced by independent modelers. Comparison of simulation models for the same work process and organization developed by Stanford vs. NPS graduate students will be used to assess and refine the model variables and scales in terms of reproducibility. In evaluation of generalizability, we model two different organizations in each domain to assure that our models have not been overfitted to just one organization or organizational setting. This evaluation provides added assurance that our work captures general concepts pertinent to all knowledge-intensive organizations.

Finally, our evaluation of reasoning, representation, and usefulness will use *gedanken* experiments (i.e., thought experiments) to compare the simulation behavior of our system to (1) the behavior predicted by theory and (2) the behavior predicted by experts. This will be a first test of how experts would use the information provided by our simulation system. We will also calibrate our models to generate predictions that match historical performance data of both organizations. Once the models are validated and calibrated, they can then be employed for prospective intervention, in which we use model predictions to help managers in these organizations to assess alternative organizational designs. This latter, prospective-intervention work is beyond the scope of the present project, however.

Through the one PI's university, which has a unique relationship with the U.S. Navy, we have ready access to the Navy's Third Fleet in San Diego and agreement for access to conduct this project research. In terms of the second site, Professor Francois Bar, the Director of the Stanford Computer Industry Project (SCIP), has agreed to assist us with identifying and securing access to a second site in year 2 of the project.

## Anticipated Impacts

Because of the interdisciplinary nature of our research (e.g., COT, engineering management, information systems), we expect the impact of our research to be broad. We expect our research will make theoretical contributions to organization theory and computational representation of knowledge-intensive processes across different domains. Practically, we anticipate tools constructed for this project would be used in both public and private sectors to improve the quality of work-process and organizational design and execution.

Our proposed organizational theory and work process analysis tools will enable enterprise designers in a given domain to represent and evaluate process alternatives consistently. Consistent modeling and assessment allows comparison of process performance and design tradeoffs that are developed by different designers. Application of the method will encourage practitioners to attempt to optimize work process plans for specific conditions while retaining the insight and spirit of well established generic plans. The interdisciplinary research method should stimulate additional inquiries in promising areas.

### Impact on Organization Theory

Our work will extend the information-processing view of the organization to include the flow and processing of knowledge in addition to information and data. To complement the long standing resource-based view of the firm (Cole, 1998; Spender, 1996), we will provide descriptive models, explanatory logic and predictive theory pertaining to the knowledge-based view of the enterprise. This view will include explicit representation and understanding of interrelations between the flow of knowledge through an enterprise and the complementary flows of information and work associated with organizational processes.

We will also increase our understanding about knowledge-intensive tasks and the way in which an information-processing framework is appropriate for these kinds of organizations. As we move into an increasingly knowledge-based economy, there is enormous societal value to better understanding how to improve organizations with better knowledge-flow processes and better understanding of the issues relevant to these organizations.

### Impact on Industry

Given the highly competitive nature of industry and the critical role that knowledge-intensive processes play in terms of sustainable competitive advantage, this project offers potential to equip firms across many industrial segments to improve performance by enhancing knowledge flow through their enterprises. Using the VDT simulation tool—as extended through this project—to analyze various organizational designs, firms in industry will have access to a new competitive weapon. They will be able to diagnose and design their work processes in a manner closer to that in which bridges, computers and airplanes are engineered than the trial-and-error or imitative approaches generally taken today.

### Impact on National Security

The U.S. Military will have a similar competitive advantage and capability, which will be particularly important as it shifts its strategy from one of platform-centric warfare to network-centric warfare (Cebrowski and Gartska 1998). Given the importance of knowledge flow in terms of military intelligence, this represents a natural extension of the project proposed here, as our theory and tools may further prove useful in terms of understanding terrorist networks and preventing military conflicts before they begin.

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