COORDINATION IN VIRTUAL ORGANIZATION OF RESEARCH & DEVELOPMENT [1]

A Working Paper

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ABSTRACT

This paper reports on a comparative case study of three ongoing research and development (R&D) projects, each conducted virtually across multiple sites and involving varying degrees of task uncertainty due to its stage on a continuum of the R&D process, from basic fundamental Research to scale-up and commercial Development. This study applies the methodology of sociotechnical systems (STS) analysis to assess the influence of virtuality and task uncertainty on the quality of the deliberations; specifically, the knowledge development barriers experienced at the various stages on the R&D continuum. Then, building on the theory of organizations as information processing systems, and referencing extant literature on the relationship between coordinating mechanisms and the efficacy of virtual work, this comparative case study has identified different types of coordination mechanisms and their impact in reducing or eliminating knowledge development barriers for differing levels of task uncertainty, from the high uncertainty of basic Research to the lower uncertainty of scale-up Development. Results of this study extend previous findings about coordination of virtual R&D that have focused almost exclusively on the product Development stage of the R&D continuum. Moreover, the study demonstrates how STS analysis can provide insights into the impact of coordination mechanisms on the performance of virtual R&D organizations. For practitioners, one implication is to explicitly design the deliberations and coordination of virtual R&D as part of the planning for projects such as multi-university research.

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1. INTRODUCTION

The National Science Foundation and other observers of the evolution of Research and Development (Industrial Research Institute, 2011; Nobelius, 2004; Gassmann et al., 2003) claim that virtual organizations spanning institutional and national boundaries have become central to the emerging practice of science and engineering. R&D is today characterized by the need to interact with suppliers, competitors, customers, stakeholders, and increasingly with cross-industry, cross-discipline network-based ecosystems. Therefore, understanding the conditions by which virtual organization can enable and enhance scientific and engineering innovation is vital to the future of R&D.

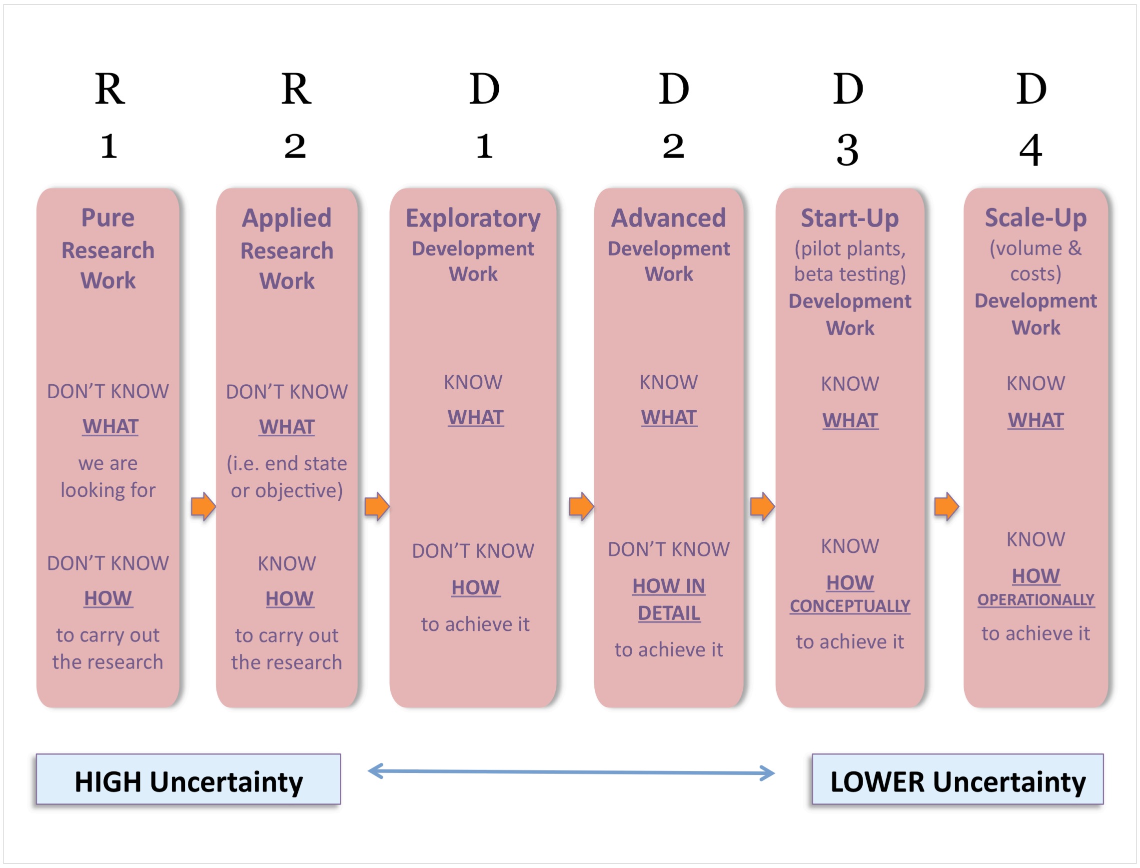
While speed and rapid prototyping are essential, factors such as staff expertise, strategic goals, and overall planning or control must be in place to assure optimal timing and pace of R&D operations. Nobelius points to organizations like 'Bell Labs' as consistently leading this process. For this study, we draw on this legacy by adapting an R&D continuum originally developed at Bell Labs (Mashey as reported in Revkin, 2008). This robust format reflects other classification systems for R&D activities (Kerssens-van Drongelen and Cook, 1997; Mankins, 1995). The model shown in Figure 1 delineates the continuum into six stages in the R&D process and describes the nature of the work and the task complexity or uncertainty at each stage.

Within the field of R&D work, the study of virtual teams and organizations (Nemiro, Beyerlein, Bradley, and Beyerlein, 2008) has focused most frequently at the later stages of 'development', particularly involving global software projects (Fabriek et al., 2008, Carmel and Agarwal, 2002; Ramesh and Dennis, 2002), and to a much lesser extent, "radical innovation" in the more 'exploratory' or 'advanced' stages of development (Majchrzak and Malhotra, 2000, 2004, 2005).

A major objective of this NSF VOSS study has therefore been to include within our sample a case of 'Pure' or 'Applied' Research along with examples of work at both the advanced and later stages of Development, and thereby, to compare the effects of virtuality across the full continuum of R&D work. We believe this wider comparison could be significant because of the differing type and degree of unknowns, and therefore, the varying degree of uncertainty associated with different stages of work in this R&D continuum.

Inasmuch as "research and development is intrinsically a learning system" (Purser et al., 1992; Carlsson et al., 1976), each stage in the continuum of the R&D process can be characterized by the degree to which participants engaged at a particular stage do or don't know the 'what' (end-state or objective) and/or the 'how' of their knowledge development and knowledge synthesizing activity. For example, both 'Pure Research' (R1) and 'Exploratory Development' (D1) entail a great deal of unknown about 'how' to achieve their work, but there is one major difference between these two stages of R&D—at the 'R1' stage, there is much less known about 'what' the end-state of the activity should look like.

Figure 1: A Six-Stage Continuum of the R&D Process[2]



1.1 Study Sample of 3 Virtual R&D Projects

Our study sample has included three ongoing R&D projects, each situated at a different stage in the continuum of the R&D process (see Figure 2). Within the field of fundamental Pure Research (R1), the "Orchid" project has involved physicists from the California Institute of Technology in partnership with scientists at other universities in Austria, Germany, Canada, and the United States. A second project, the "Uniform Data Set" was initiated at the Advanced Development (D2) stage by staff at the University of Washington in conjunction with 29 Alzheimer's Disease Centers across the United States, and has been implemented through later stages of the R&D process. The third virtual organization involves some Start-Up (D3) and mostly Scale-Up Development (D4)—art asset production, engineering and testing—by a "Large Video Game" developer with vendors in the Philippines, China, India, Sweden, and the United States.

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[2] Bell Laboratories' R&D Portfolio Management profile, as reported by John Mashey to Andrew Revkin (NY Times, Dec 12, 2008), and adapted by Carolyn Ordowich (personal communication, Mar 26, 2009).

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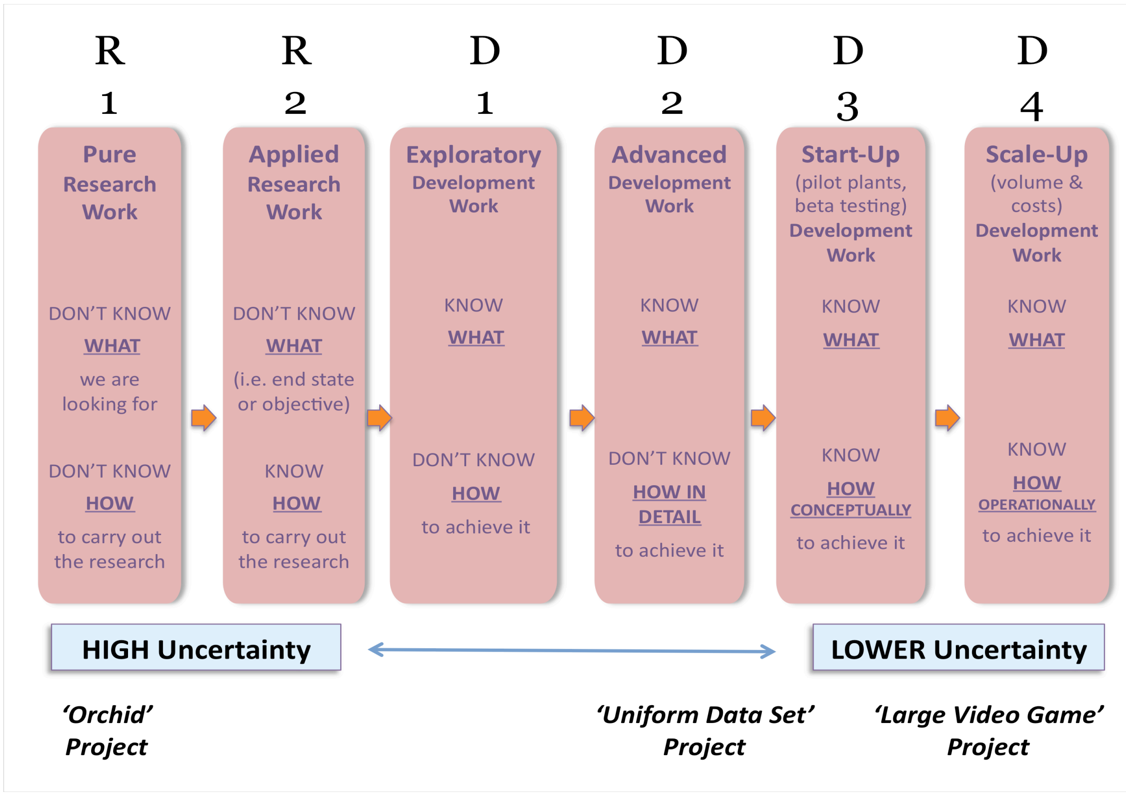
Figure 2: Location of Case Study Projects on the R&D Continuum



Each of these projects has been conducted in its own virtual organizational setting. In terms of the nature of virtuality, (Lipnack & Stamps, 1997; Chudoba et al., 2005; Gibson & Gibbs, 2006; Malhotra & Majchrzak, 2004; Schweitzer & Duxbury, 2009; Dixon & Panteli, 2010), this has meant (1) work on interdependent (knowledge-based) tasks, (2) by participants dispersed across space and time, (3) unable to collaborate face-to-face all (or most) of the time, and thus, (4) with a relationship primarily conducted over technology.

2. THEORETICAL BACKGROUND

2.1 Sociotechnical Systems (STS)

As well as the notion that an R&D work organization is a "learning system" at a particular stage in a continuum of task uncertainty, this comparative study has been based upon the concept of work organizations as open "sociotechnical systems". Sociotechnical Systems (STS) theory offers robust theoretical and practical lenses to examine *both* the social and technical subsystems of work, and how their design and quality of fit influence work organization effectiveness (Emery, 1959; Ackoff, and Emery, 1972; Pasmore, 1988).

"First-generation STS" theory established a successful track record in design of manufacturing and chemical process industries (Davis and Cherns, 1975; Emery and Thorsrud, 1969; Rice, 1953), leading to a set of work organization design principles (Cherns, 1976). With the growth of service industries and "office technology" in the 1980's came a shift to knowledge-intensive, non-routine work. Non-routine work systems (such as those found in R&D) are typified by nonlinear conversion of data into information and information into knowledge; multiple and often concurrent tasks with high degrees of reciprocal interdependence; and, a high degree of specialized expertise and professionalism (Pava, 1983).

"Second-generation" STS theory for non-routine work processes has focused on 'deliberations' as the unit of analysis (Pava, 1983; Taylor, Gustavson, and Carter, 1986). Deliberations for non-routine knowledge work are "the equivalent…of unit operations for the long-linked [manufacturing and process] technology" (Trist, 1983). Similar to the way that a linear manufacturing conversion process is achieved through a sequence of 'unit operations', (each of which is a cluster of production steps that change the state of raw material into an interim product), the overall nonlinear conversion of ill-defined inputs such as product ideas into an integrated product design is propelled through a complex stream of interlocked 'deliberations', (each of which is itself a sub-transformation of equivocal information and knowledge into defined outcomes).

In his study of non-routine office work, Pava (1983) described deliberations as "equivocality reducing events", i.e. choice points that are critical to work systems involving knowledge generation and knowledge utilization. From this general description, Purser (1990) defined deliberations in product development as "social interactions in which knowledge is exchanged to define or solve a problem, make a decision, or implement a solution". However, deliberations are not simply the equivalent of decisions or meetings; rather, they are sense-making exchanges (Weick, 1995), communications and reflections in which people engage to reduce the equivocality of a problematic issue.

A deliberation is identified by the existence of an equivocal *topic*, which is explored in different types of *forums*, involving a particular group of *participants* who contribute and/or take-away key information. Deliberation analysis assesses the composition of participants within forums, and the interpretative dynamics among interdependent parties who must forge a "discretionary coalition" (Pava, 1983) to make intelligent trade-offs from their respective values, priorities, and cognitive orientations (Tenkasi, 1994; 2000).

Previous studies have demonstrated the value of using deliberation analysis as a method for identifying the sources and incidences of failures and delays in product development (Pasmore and Gurley, 1991; Purser, 1990, Purser, Pasmore and Tenkasi, 1992; Shani and Sena, 2003; Tenkasi, 1994; 2000). These studies (mostly of co-located work) established that new product development effectiveness is characterized "by deliberations that enable organizational members to *acquire, share, interpret, and retrieve* the knowledge that they need for resolving equivocal problems" (Purser et al., 1992).

STS analysis of breakdowns in the effectiveness of input-output conversion processes has utilized, for linear processes, the concept of 'variance', an out-of-norm event involving a deviation from a predetermined standard (Pasmore, 1988), disrupting the steady state of production "in the direction of reduced productive efficiency" (Herbst, 1974). However, in non-routine knowledge work, there is no norm from which deviations are identified (Taylor, 1989) and there is no steady state of knowledge generation. Nevertheless, as Pava (1983) identified in his groundbreaking study of office work, non-routine work is often plagued by "information gaps" at which deliberations go awry in the forums for each topic.

Building on Pava's work, others have identified the source of such information and knowledge "gaps". For instance, through analysis of deliberations in two product development projects co-located within a major consumer products company, Purser et al. (1992) identified four main categories of "*barriers*" obstructing and delaying collaborative knowledge development: (1) *knowledge sharing and planning* barriers, such as lack of cooperation, missing parties, or unrealistic timeframes; (2) *cognitive frame of reference* barriers, associated with differences in language, values, etc.; (3) *knowledge retention and procedural* barriers, such as lack of technical documentation or lack of external consulting; and, (4) *knowledge acquisition* barriers resulting in a lack of available knowledge.

Now, for this comparative case study, these concepts of 'deliberations' and knowledge development 'barriers' have been extended to the analysis of work, specifically R&D, conducted in *virtual* organizational settings.

2.2 Coordination Mechanisms

Our interest in learning how virtual organization can enable R&D has also led us to examine coordination, i.e. "managing dependencies between activities" (Malone and Crowston, 1994). Coordination has been described as "the major challenge" of global software development and other types of virtual R&D (Herbsleb, 2007; Ramesh and Dennis, 2002).

A connection between coordination mechanisms and the possibility of mitigating knowledge development barriers is based upon theory of organizational information processing (Galbraith, 1974; Daft and Lengel, 1986; Weick, 1979, 1995). This theory postulates that structural mechanisms for coordination must provide the means to handle the amount and richness of information processing required by the *uncertainty* and *equivocality* of an organization's task, interdepartmental relationships, and environment.

Inasmuch as "organizational structure must perform the major functions of facilitating the collection of information…as well as permitting effective processing of information" (Daft and Lengel, 1986), coordination mechanisms can make a major difference for how well deliberations in non-routine work incorporate the right information and knowledge, and the right participants at the right time. Indeed, as one of the main proposals for a best match between non-routine technical and social sub-systems, Pava (1983) recommended "structural changes in the organization pertaining to responsibilities and *coordination* that enhance major deliberations and their associated coalitions".

Specific mechanisms to permit coordination have been proposed by Galbraith (1974) and others using an information processing view of organization design, starting with goal-setting, hierarchy, and rules, and extending to development of lateral relations to increase the capacity to process information. In a similar format, Mintzberg (1979, 1983, 1998) proposed a model with six broad categories of coordination: (1) mutual adjustment; (2) direct supervision; and standardization of (3) skills, (4) work processes, (5) results, and (6) norms. However, more specific to global software projects, and potentially most relevant for our study of R&D work, Sabherwal (2003) condensed many classifications identified in the information systems literature into a continuum of four main types of coordination mechanisms: (1) standards; (2) plans; (3) formal mutual adjustment; and (4) informal mutual adjustment.

Coordination through "standards", (very much like the various forms of standardization identified by Mintzberg), relies upon pre-specification of rules, routines, techniques, and targets. Coordination through "plans" (which is related in part to Mintzberg's concept of standardization of output) is another approach that is mostly impersonal in nature once implemented. By contrast, in both forms of "mutual adjustment", coordination is made possible through interpersonal communication, feedback and interaction. Nevertheless, in one form, the adjustment is made in the "more structured and formalized fashion" of design review meetings or liaison roles, as compared with the informality of impromptu or face-to-face communication. Another difference between the forms of mutual adjustment involves a distinction made by Nidumolu (1995) between "vertical" coordination (through authorized entities) and "horizontal" coordination (through peer interactions).

In addition to defining key modes of coordination, theory and empirical research (Thompson, 1967; Galbraith, 1974; Van de Ven et al., 1976; Weick, 1979; Argote, 1982; Daft and Weick, 1984; Kraut and Streeter, 1995) have identified the level of task uncertainty and the degree of task equivocality (or ambiguity) as key determinants of the requirements for specific coordination mechanisms. In broad terms, the proposition has been that "more informal, communications-oriented" mechanisms are more suitable "when uncertainty is greater: during the requirements analysis phase". On the other hand, more impersonal, "more formal, control-oriented" mechanisms are "most suitable when uncertainty is less during the design, implementation, and testing phases of a project" (Sabherwal, 2003).

With respect to *virtual* organization, Sutanto et al. (2011) found a "fit" between types of task dependence (with increasing uncertainty) *and* optimal task coordination portfolios in global virtual teams engaged in software development. Lower task interdependence (pooled or sequential) was primarily coordinated by standards and plans, while higher task interdependence (reciprocal or team) required various forms of mutual adjustment. Gassman et al. (2003) found a similar correlation between a set of factors incorporating different levels of uncertainty *and* four distinct forms of virtual team organization used in multinational companies to execute virtual R&D projects. In summary, there is considerable prior literature suggesting that task uncertainty (i.e. lack of information) is an important factor influencing coordination mechanisms.

3. METHODOLOGY AND RESEARCH SITES

The purpose of our research has been to develop grounded theory, not to test it. Thus, we employed a theoretical case sampling methodology (Eisenhardt and Graebner, 2007) that entails selecting cases particularly suited for illuminating theoretical constructs. Our study sample of three R&D projects, each at a different stage in the R&D process, and together covering the full breadth of the R&D continuum has provided an opportunity to apply and build upon this theoretical background, specifically in the context of virtual R&D settings.

An extensive review of the literature in sociotechnical systems theory, virtual organization, and organizational information processing helped frame the context and focal questions for this research. Using the literature in these fields as background in developing the protocols, a series of scoping interviews were then conducted with each organization to gain an understanding of projects and the participants in the virtual work.

Our methodological approach was essentially to utilize the diagnostic steps of sociotechnical systems analysis for non-routine knowledge work (Pava, 1983). Our 'scoping' interviews were, in effect, part of an initial scan of each virtual organization, to map the boundaries of the system, major work activities/projects, and key stakeholders.

Once having chosen a specific project to investigate in greater depth, we analyzed the technical subsystem of the work. This analysis included listing the major deliberations, identifying the different forums in which these deliberations were conducted (in person, videoconferences, teleconferences, email, etc.), determining other tools and procedures used to gather, record and circulate information, identifying the participants in these key deliberations, and surfacing knowledge barriers or information gaps in the deliberations.

To analyze the social subsystem within which the major deliberations occurred, we developed questions that addressed issues such as the roles and responsibilities of parties involved in deliberations, their divergent and common perspectives, key influencers or participants, means of building support for decisions, how they manage conflicting interests or perspectives, and how all of these factors impact the quality of deliberations.

The interview protocols established by the VOSS research team for the comparative study as a whole were customized to gather data in a manner feasible and appropriate for each research site. Sometimes, interviews were supplemented by extensive document research or an electronic survey. However, in all three cases, structured interviews were conducted with a cross-section of people from each virtual R&D project. When it was possible the interviews were conducted in person; otherwise they were conducted by telephone. Also when possible, each interview was conducted by two members of our research team.

With the consent of the interviewees, the interviews were recorded and transcribed so that other members of our VOSS research team could listen to the interviews and analyze the results. Another method that facilitated the comparison of data across research sites was that at least one of the two or three investigators studying each site was also a member of another sub-team investigating a second of the three virtual R&D projects in our study sample. What follows is specific description of our study methodology for each project/site.

3.1 Large Video Game (LGV)

In the spring of 2010, we began our research with LVG Inc., and conducted initial 'scoping' phone interviews with the General and Project Managers at LVG's North American studios to select a specific project for case study. An on-site visit and interviews were then conducted in the late summer with 14 project team members in one of their facilities, including the General Manager, Project and Program Managers, Development Managers, Artists, Software Engineers, Creative Director, Audio Engineers, Outsourcing Managers, and Quality Assurance Managers.

At two project milestones extending over two of their production runs, follow-up telephone interviews were conducted with the Program Manager, Development Managers, Outsourcing Manager, and Artists and Engineers. These interviews provided additional detail about the development process and team members' perceptions of critical deliberations.

For the final eight months of the first production run, GAME X 1, electronic surveys were administered to these team members at the end of each three-week cycle in their agile development process. An additional electronic survey was also conducted with five key vendor organizations located in Asia during a two-month period to assess how both parties to the virtual relationship viewed deliberation efficacy and how well potential challenges were met. An extensive interview was also conducted with a sixth vendor.

Specific survey questions inquired about the frequency and mode of communication, key topics, roles of participants involved at both LVG and the vendor location, perceived effectiveness of communications and ratings of which factors and to what degree (language, time zone differences, data transfer, etc.) may have been impediments. Questions also evaluated the nature of tasks (routine or non-routine) and their degree of completeness as performed by the vendors in each three-week development period.

Follow-up phone interviews with Program and Development Managers were used to gain feedback on the survey results and on our preliminary analysis of deliberations in the development process, as well as to obtain an update on the final development stages and the results associated with release of the GAME X 1 product.

During the autumn of 2011, detailed interviews were conducted with the Project and Program Managers, Outsourcing Manager, and Quality Assurance Manager, in order to learn the outcomes of their GAME X 1 project debrief and related process innovations to be used for work with key vendors in development of the next production run, GAME X 2. By January 2012, we received feedback in final interviews with the site LVG Managers, regarding the impacts of the outsourcing process changes made for the GAME X 2 project.

3.2 Uniform Data Set (UDS)

We started in the spring of 2010 with an initial scan to discern the mission and governance processes of the Alzheimer's Disease Centers (ADC) research network. The scan was conducted through review of available documentation on the major research initiatives and key stakeholders, observation of the 2010 ADC Directors' meeting in San Francisco, and interviews with the Principal Investigator of the National Alzheimer's Coordinating Center (NACC) and the NIA's Program Director for the Alzheimer's Disease Centers.

Informed by this preliminary mapping of the ADC research network, we chose the UDS as the specific project to investigate in greater depth. We then constructed a framework for interviews with the identified key stakeholders in order to analyze the technical and social subsystems of the UDS project that involved 29 Alzheimer's Disease Centers.

Since the structure of the UDS had already been established prior to our research and many of the early implementation challenges had been addressed, we conducted retrospective interviews and secondary data searches to understand the development process, the scope of involvement of various personnel, and the kinds of decisions and actions taken to reach consensus on the UDS.V1. However, at the time we conducted our interviews, the NACC and the Clinical Task Force were in the process of revamping the batteries of instruments and measures for the UDS.V3 and we were able to gather contemporaneous insights on how they were conducting this task in a virtual environment. We also interviewed ADC researchers about current use, decisions, and applications of the UDS to gain a perspective on how deliberations related to it have changed over time.

A total of 12 (60 to 90-minute) telephone interviews were conducted during the winter of 2010 and spring of 2011 with a cross-section of ADC directors, principal investigators, clinical core directors, neurologists, psychiatrists, biostatisticians, and other members of the research teams. These interviews were transcribed and members of our research team analyzed the content to identify common themes regarding key deliberations, the efficacy of technology-mediated and face-to-face forums, barriers to knowledge development, and coordinating mechanisms used to address them in support of the UDS project.

3.3 Orchid Project

In 2010, the VOSS research team also opened discussions with Caltech's Micro & Nano Photonics Research Group in the Applied Physics department. This research group had previously agreed and expressed an interest to participate as a site in the VOSS NSF project. However, a 'scoping' discussion that extended over several months was required to determine the most appropriate multi-site research activity to focus upon. Eventually, despite the challenges of their transcontinental collaboration in a DARPA-funded theoretical and experimental research program entitled 'Orchid', Caltech's Photonics Research Group and the University of Vienna's Quantum Optics Group agreed to participate as the third virtual R&D project in this VOSS comparative study. At the same time, the Principal Investigator at Caltech also facilitated the VOSS team's contact with scientists from other universities in the international network involved with the Orchid program.

Early in 2011, a member of the VOSS research team made a two-day on-site visit to the Caltech laboratories and then conducted face-to-face interviews with the Principal Investigator and Caltech graduate students heavily involved in the Orchid project. Plans were also made for phone interviews with faculty and graduate students located at the University of Vienna laboratory, and with European and Canadian members of the Orchid project team of theoretical physicists. Most of these interviews were held during Phase One of the project, in the summer and autumn of 2011. It was emphasized by the Orchid project Principal Investigator that PhD students and post-doctoral associates working in the laboratories in Europe and Caltech were the individuals most involved in the day-to-day process of this scientific collaboration, and thus, would be preferred subjects for interviews in this study.

Interview protocols were developed to identify key deliberations in the process of fundamental research, the qualitative nature and frequency of use of various media for communication among project participants, and perceptions of the nature and challenges of this early stage scientific collaboration.

A second round of interviews were conducted during the start of Phase Two of the project, in the autumn of 2012. Overall, during an elapsed period of three years, approximately 20 (60-90 minute) interviews were conducted in person or by phone, involving two members of the VOSS research team and one subject/participant of the Orchid project. Interviews involved all of the key participants in this collaboration between the Micro and Nano-Photonics Group at Caltech and the Quantum Optics and Nanophysics Group in the University of Vienna, as well as members from a team of theoretical physicists distributed across Germany, Canada, and the United States.

4. FINDINGS FROM CASE STUDIES

Building upon background theory and using the STS framework of analysis, the main findings from our comparative study can be summarized for each of the three virtual R&D projects in terms of: (1) key *deliberations*; (2) key *knowledge barriers* affecting these deliberations in a virtual setting, and (3) the most significant *coordination mechanisms* helping to overcome these barriers, and thereby leading to positive outcomes as perceived by participants in terms of traditional performance measures of cost control, on-time delivery, and product or research quality and productivity (Prasad and Akhilesh, 2002).

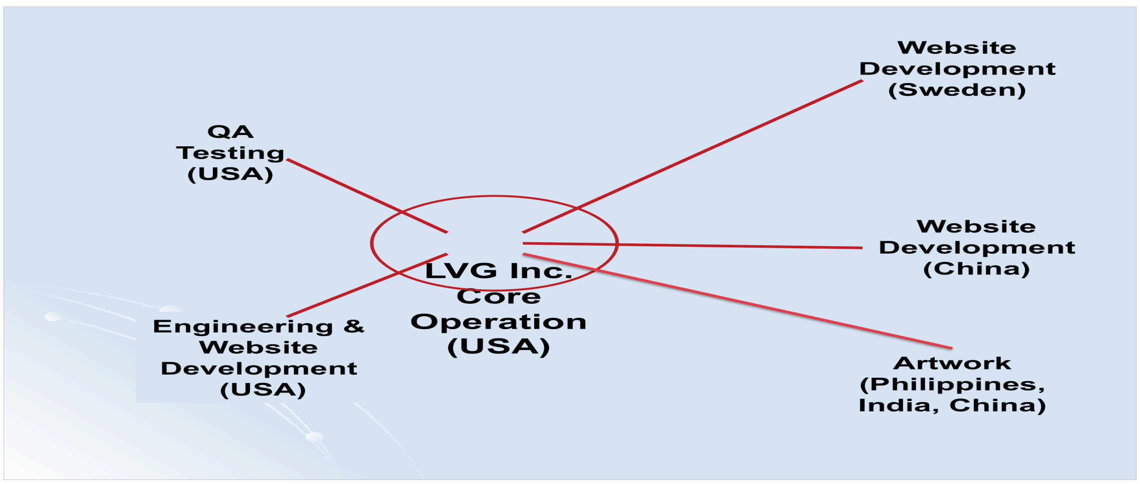
4.1 'Large Video Game' (LVG Inc.)

This commercial product development process ("D3-D4" on the R&D continuum) is critically time-bound to game feature completion. The product platform for the video game that was the focus of our study was established over several generations and years of development—during the period of our study, two product versions of the game, GAME X 1 and GAME X 2 were developed and released.

In the period between the two product cycles, LVG Inc. instituted a number of development process improvements. However, the overall Development phases remained--Concept discovery, Design and Planning, First Production and Final Production, an intense Testing and De-Bugging phase, and Shippable Build of the product for Delivery. Production includes Art Assets (e.g. 3D animated characters), Engineering (e.g. new and revised programming for the source code of the game), Website Design (e.g. user interface features for the game's interactive website), and overall Quality Assurance.

The development process has been based out of the United States in a virtual organization of participants dispersed widely across the globe (see Figure 3), most often with no economically viable possibility of face-to-face interaction.

Figure 3: Virtual Organization for LVG Product Development



Three major Art Asset vendors were involved in both generations of the product, one located in the *Philippines*, one in *China*, and another in *India*. More complex Engineering and Website Development have been outsourced on a more limited basis, for the first-generation product to *American*-based vendors and a third vendor in *Sweden*, with a change in the second-generation development process to only one *American* vendor and one in *China*. During the later phases of both product generations, final testing and de-bugging was conducted at a site affiliated to LVG Inc. in the *United States*, though located at considerable geographical distance from the core offices for design, production and final product delivery. Despite the geographical distance, most of these vendors were quite familiar to LVG Inc. Moreover, the overseas vendors are not small-sized enterprises—they are world-class facilities serving global clients.

4.1.1 Deliberations

In terms of the R&D continuum, *most* of the work conducted within this virtual organization, especially production of art assets, has been "D4" development work. LVG Inc. core staff knows 'what' they want developed (with very clear specifications), and they know how it can be achieved operationally through the prototypes that they have built. Art

Asset vendors described their work in this product development as "routine" or as "routine, with a minor degree of discretion".

"D3" type development occurs with more of the systems engineering and website work, where internal LVG Inc. staff knows what they want to have developed, but their expertise is limited to knowing only conceptually how to achieve these outcomes. In their virtual relationship with LVG Inc., Engineering and Website vendors described their work as "routine, but requiring discretion" or "non-routine, with moderate degrees of freedom" and in one instance, "with high amounts of discretion".

Nevertheless the *key deliberations* involving LVG Inc. staff and external vendors for virtual Art Production are very similar for virtual Engineering or Web/online game development; namely, they are key 'choice points' that occur in the front-end of the process. 'Vendor selection' is a deliberation topic of primary significance in all these aspects of game development. Another key deliberation topic involving LVG Inc. staff and vendors is 'defining and estimating' the outsourced project work. A third key deliberation specifies 'documentation and requirements'.

4.1.2 Knowledge Barriers

For virtual art production, (i.e. "D4" development work), during both generations of video game development observed in this study, the occurrence of key *knowledge Barriers* in these deliberations was much less evident than in all of the other development work conducted through virtual organization. Despite 'far-flung' location of Art Asset vendors in parts of Asia very distant from the core LVG Inc. operation, potential limiting factors of time zone, language and national culture differences, all proved to be insignificant barriers to sharing or utilizing knowledge in key deliberations about expectations and requirements for Art Production.

For virtual Engineering and Web/Online systems, (i.e. "D3" development work), significant barriers did arise, particularly for the earlier version of the product development observed in this study. Issues included unclear expectations, unrealistic timeframes, delayed data transfer, and lack of documentation.

Barriers in knowledge-sharing occurred in systems Engineering because of IP issues by which LVG Inc. core operations could not share vital source code with vendors. For "D3" type web development, lack of planning meant that expectations about requirements quite often diverged and were not always effectively resolved between LVG Inc. and vendors. In deliberations about the selection of web development vendors, there was also an initial failure to utilize knowledge that other divisions of LVG Inc. had about reliable capabilities and technical set-up in companies distributed across the vendor community.

Knowledge barriers associated with different frames of reference also affected Quality Assurance. Although the remote test center and LVG Inc. core operations are part of the same company, their respective staff had different understandings about the 'speed' or pace expected for work completion. Also, part-time and high turnover Testers at the remote test center did not have access to the 'tacit' knowledge held by core staff at LVG Inc. regarding critical features of the game architecture; consequently, some high severity game "bugs" were not initially tested, though they were eventually discovered by core operations prior to final product delivery.

4.1.3 Coordination Mechanisms

The differences between the product development experience of virtual Art Production and virtual Engineering or Website Development are very illuminating. The relatively routine and mature work processes of virtual Art Production enable clear expectations for LVG Inc. and its vendors about "what good looks like" in task deliverables. Key deliberations in virtual Art Production can therefore involve the parties' gaining shared agreement on "standardization of outputs", through communication in "semantically rich" media of screen shots, visual targets, emails, and extensive digital documentation. This method of coordination is similar to the experience of standardized outputs for "object-oriented teams" in global software development as reported by Ramesh and Dennis, (2002).

In the one instance during our study when an art asset vendor did fail to provide the quality of aesthetic that was needed, it was due to the art work prototype's lacking in certain detail, followed by the failure of LVG Inc. to use test procedures to track vendor errors. Subsequently, LVG Inc. changed its work practices to increase the detail in similar prototypes. Also, a representative of LVG Inc. made a site inspection to verify the vendor's capabilities. Normally, an initial inspection of a vendor site is done to verify security. It can also be a sign of respect to vendors as "an integral part of [the LVG Inc.] team".

For Engineering and Web/Online game development, however, LVG Inc. staff will most often *not know* the details of 'how' the outputs are to be achieved. Moreover, the quick feedback that is possible in-house, standing over each other's computers and making 'live' corrections to any misunderstandings or other knowledge frame of reference issues has proved to be unavailable with Engineering vendors in a virtual organization. This problematic situation resulted in delay and cost overruns for GAME X 1, the first of the two product versions of game development that we observed in this study of LVG Inc.

However, in the time period between these two product development runs, LVG Inc. staff made some important changes to alter the coordination of Engineering and Website Development. Starting with vendor selection, deliberations are now coordinated between LVG Inc. and representatives from other divisions of the company to pool all available 'intelligence' about potential vendors. There is now on-site verification by LVG Inc. to ensure vendors have the proper technical set-up before any selection is made. New technical arrangements have also helped overcome the intellectual property issues that previously constrained the sharing of game source code with Engineering vendors--a "cloud-based desktop" solution provides vendors access to source code and the ability to integrate new code, while preserving LVG Inc. proprietary control.

To reduce barriers related to expectations and realism of timeframes for Engineering and Website projects, LVG Inc. now requires its staff to develop more robust plans clarifying project scope before any vendor contractual negotiations. Furthermore, projects are "chunked" into phases, and vendors must provide schedules for specific deliverables. Finally, to facilitate timeliness, availability, and consistency of participation by LVG Inc. staff in deliberations with Engineering vendors throughout the development process, LVG Inc. has made a structural role change to designate a single "product owner" contact person assigned to resolve issues for each vendor for a specific engineering assignment.

With respect to the issues in Quality Assurance work, numerous steps have been taken to close the gaps in knowledge coordination. The Lead Tester at the remote test center has a closer liaison role with LVG Inc. core operations. The Test Lead also reinforces LVG Inc.'s increased Tester training (i.e. "standardization of skills"). At the same time, work processes at the remote test center have been standardized through greater use of audited test scripts. Finally, LVG Inc. has made an effort to increase the "ownership" and tacit knowledge of the remote Testers—they can now videoconference into production meetings and 'scrums' at LVG Inc. core operations, and thus learn about various game features as they are being developed and evaluated.

Given all of these changes in coordination and the development process, (see Table 1), significant barriers to sharing and utilizing knowledge with Engineering and Website vendors were eliminated or reduced. Consequently, for GAME X 2, the second product run, LVG Inc. and their vendors completed the project on-time, on-specification, and on-budget.

Table 1: STS Analysis of 'Large Video Game' Project

Start-up (D3) & Scale-Up (D4) Product Development

Key DELIBERATIONS	Knowledge Development BARRIERS	Significant COORDINATION Mechanisms
-Vendor Selection -Defining & Estimating Project Work -Detailing Documentation & Requirements	-Failure to Utilize Knowledge (within the wider organization) about vendor capabilities -Differing Frames of Reference creating diverse expectations -Lack of Knowledge Sharing due to intellectual property issues	-Initial On-Site verification of vendor set-up -Standardization of output -Standardization of skills—Tester training -Standardization of work processes—QA test scripts -Plans for project scope 'chunked' into phases with detailed schedules -'Product owner' Role to resolve vendor issues -Videoconference participation in Production Meetings -IS 'cloud' computing Technology solution

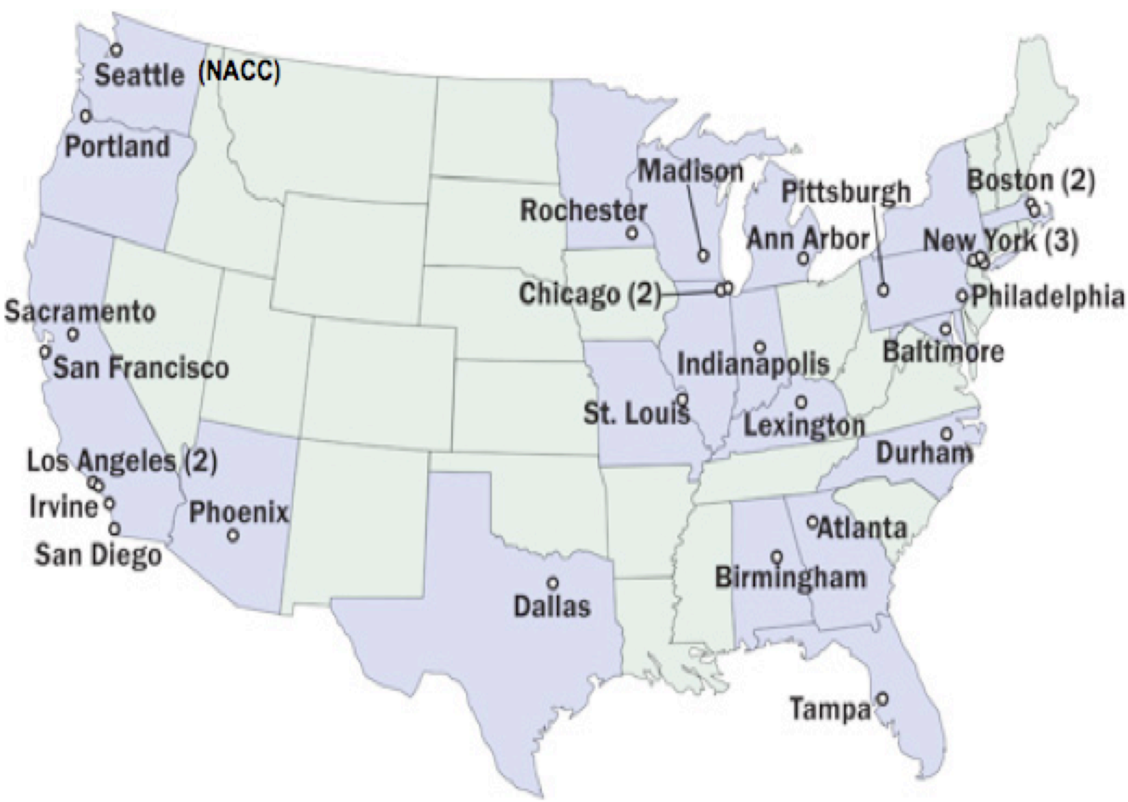
4.2 Uniform Data Set Project

This project has involved the design ("D2") and ongoing maintenance ("D3-D4" on the R&D continuum) of the Uniform Data Set (UDS), a longitudinal database of clinical and neuropathological information on Alzheimer's patients in the United States, sponsored by the National Institute of Aging (NIA). The evolution of the UDS can be traced back to a minimum, 50 element data set that was maintained at Rush Presbyterian Medical Center, Chicago (1984-1999). However, quality control of this minimum database suffered, resulting in a missing data rate of 20-30%.

Recognizing the need for a reliable and more robust database as a key resource for Alzheimer's research, the NIA established in 1999, a National Alzheimer's Coordination Center (NACC) at the University of Washington. The initial NACC mandate was to encourage and support more effective collaboration among Alzheimer's Disease Centers (ADC) throughout the United States, in development and utilization of a Uniform Data Set.

In 2005, the NACC implemented the standardized UDS, with a much-expanded total of 700 common data elements that a network of 29 Alzheimer's Disease Centers at medical institutions across the United States (see Figure 4) were required to contribute via a web-based data input system. More recently, the UDS has grown to include 725 variables in longitudinal data on 80,000 Alzheimer's patients.

Figure 4: Network of Alzheimer's Disease Centers & National Coordinating Center



4.2.1 Deliberations

Since 1999, the NIA-funded National Alzheimer's Coordinating Center at the University of Washington in Seattle WA has worked with a Clinical Task Force of Alzheimer's Disease Center directors and clinical core directors to develop and update the standardized content of the UDS. The selection of data points is important because it determines the longitudinal information available for researchers to use in their investigation of Alzheimer's and related conditions. Thus, the question of what data to include in the UDS was initially a key deliberation, and has continued to be triggered by advances in science and technology.

Each Center's daily data collection is reported to the NACC. Standardizing this process (including formats to gather the data, frequency of submission, etc.) was a critical piece in the development of the UDS at its inception. The UDS is based upon a set of standardized instruments. Since the UDS was established, the charges for use of these instruments has increased dramatically enough that efforts have been made to determine whether the UDS and the NACC should create their own dedicated instruments or continue to pay the rising costs. Therefore, the topic of how to collect the UDS data has been a recurring key deliberation, with many sub-topics, conducted in several forums, involving extensive participation from Center staff, directors, and the Clinical Task Force.

Given the substantial, expensive work required to create the Uniform Data Set, and all of the time and resources contributed by each ADC to maintain the UDS, another significant deliberation topic has been how to distribute and use the UDS data for research. A controversial sub-topic initially resolved but arising periodically, concerns right of access to UDS data beyond the 29-member ADC network.

4.2.2 Knowledge Barriers

The elevation of the original minimum data set to the Uniform Data Set standard was a development task fraught with difficulties and challenging questions. Initially, many of the Alzheimer's Disease Centers were resistant to the 'coordinating center' concept. The requirements to use standardized data collection approaches as part of the UDS was viewed by some researchers/clinicians as an imposition over being able to collect data that is best suited to their unique research interests and needs.

This holdover from the minimum data set (that did not have the same degree of standardized elements) created significant barriers to knowledge sharing in the early stage of deliberations about which items were to comprise the enhanced Uniform Data Set. Each researcher or ADC had invested heavily to develop their own specific measurements to gather the data that they determined to be most valuable to their own studies. When the UDS was set-up, not all of these data items could be included, and the challenge was to reconcile the tensions that arose when the final selection was made. In the words of one scientist, "*the trade off is the perceived value of data from tens of thousands of people collected uniformly, versus the value of 29 centers pursuing individual, local and maybe smaller consortium expertise*."

In creating an integrated system for the collection of data, other knowledge barriers have arisen from the different frames of reference associated with the diverse disciplines involved, for example, in the formulation of the items submitted to the database. At each Alzheimer's Disease Center, data have to be collected and analyzed by a multi-disciplinary group--clinicians, neurologists, statisticians, neuropsychologists, epidemiologists, nurses and research staff—whose communication is further complicated by dispersion of people across separate departments and buildings in one medical facility or university campus.

This multi-disciplinary variety is nonetheless a perceived strength of the UDS. However, it has also increased the challenge of inclusion of a sufficient range of disciplinary perspectives in NACC-level deliberations. Occasionally, there has been a failure to utilize the knowledge of one or more specific disciplines, for example, bio-statisticians and epidemiologists, in deliberations on topics such as the choice of diagnostic instruments.

4.2.3 Coordination Mechanisms

The NIA learned from the earlier experience with the minimum data set. In order to develop a more robust, more reliable uniform data set drawing upon a large number of independent, somewhat competitive research data sources, the NIA created and funded a new coordination mechanism. The National Alzheimer's Coordinating Center has provided the 'space' and infrastructure for effective deliberations on the design and continuous refinement of the UDS, working with the Clinical Task Force as well as professional steering committees coordinating discussions across the ADC network. These deliberations have been participative in style, and involved leaders in the Alzheimer's research community with strong source credibility plus a commitment to the success of the network and its transcendent purpose, i.e. to address Alzheimer's disease.

Particularly in the earlier, advanced development stage ("D2") of the UDS, coordination also benefited from the "reticulist" (Power, 1973; Friend, Power and Yewlett, 1974) or network builder (Hargadon, 2003) skills of specific individuals in key roles within the NACC and NIA. These individuals have utilized their influence and ability to build relationships and overcome barriers across organizational and disciplinary boundaries so as to forge consensus and innovation on some very contentious issues.

Furthermore, on an ongoing basis, the NACC coordinates the bi-annual face-to-face meetings of the ADC directors and staff. Although infrequent, these face-to-face meetings are one key part of a dense set of relationships among participants in the ADC network. Overall, these relationships have strengthened the will and ability for collaborative development of the UDS. This collaborative 'spirit' has been further strengthened by a larger shared 'mission' to reduce or solve Alzheimer's disease.

Other mechanisms include the limited funds that the NACC provides to support collaborative research projects among Centers contributing to and using the UDS. The NACC exercises additional financial leverage through modest annual payments made to Centers, on the condition that the volume and quality of data they submit meet UDS timelines and other standards. For some, but not all, of the Alzheimer's Disease Centers, these financial factors have mitigated barriers to knowledge-sharing and reinforced the coordination of data collection for the UDS ("D4" on the R&D continuum) that is achieved primarily through the standardization of output.

Despite formidable scientific and logistical challenges, coordination efforts (see Table 2) have enabled the UDS project to prevail well beyond what was achieved with the original minimal data set.

Table 2: STS Analysis of 'Uniform Data Set' Project

Advanced (D2) & Scale-Up (D4) Development

Key DELIBERATIONS	Knowledge Development BARRIERS	Significant COORDINATION Mechanisms
-Selection of Data Points	-Lack of Knowledge Sharing due to divergent research interests/priorities	-National Coordinating Center -'Network Builder' Roles and skills
-Choice of Diagnostic Methods & Instruments	-Failure to Utilize Knowledge from a full range of disciplines	-Professional steering committees -Clinical Task Force -Bi-annual face-to-face Conference Meetings
-Data Collection & Analysis	-Differing interpretative Frames of Reference based upon diverse technical disciplines	-Standardization of outputs -Reporting Requirements for volume and quality of data -Financial incentives

As a testament to the success of the Uniform Data Set, hundreds of research projects and publications have used NACC data. Indeed, the UDS project has contributed to a "culture of collaboration" among Alzheimer's researchers and received acclaim in the popular press[3].

4.3 'Orchid' Project

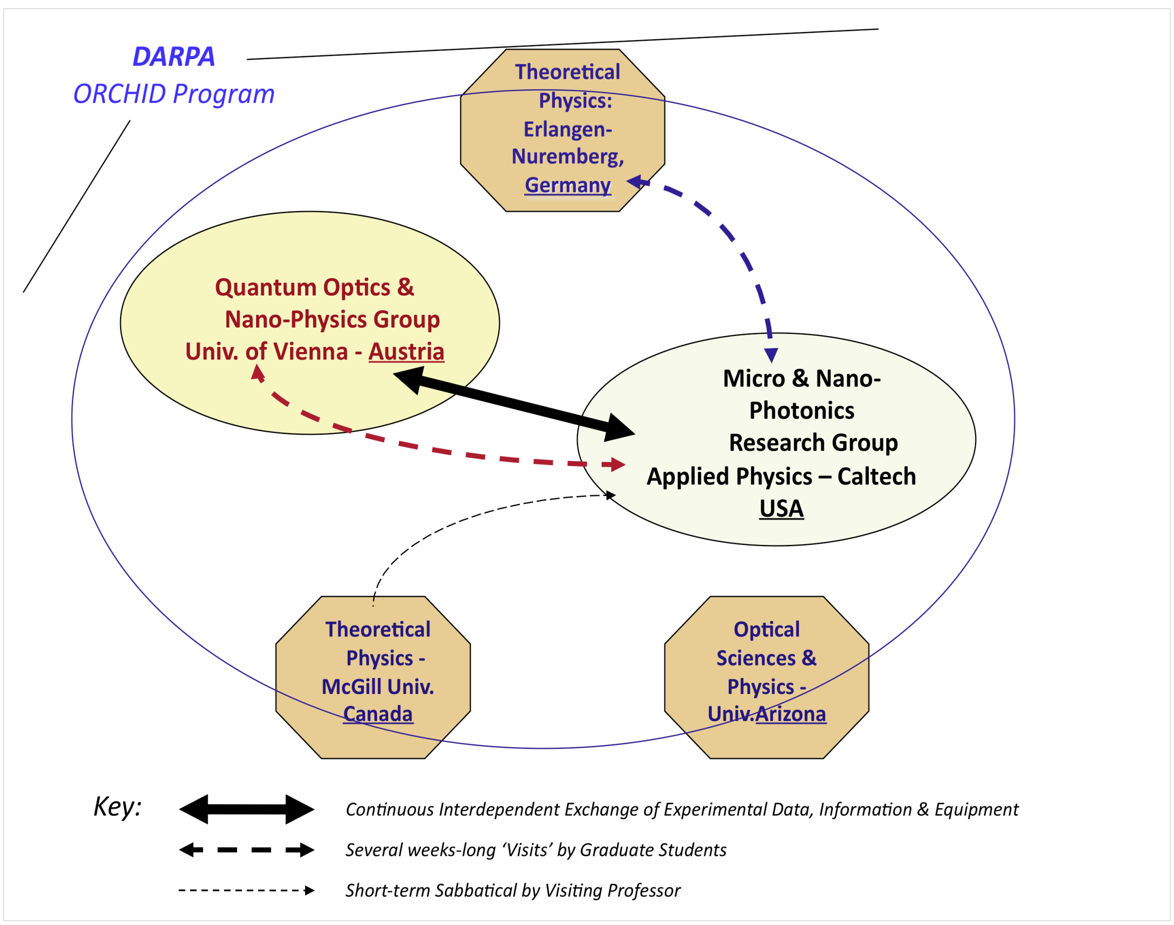
The focus of this case study was a transcontinental, multi-university collaboration by a team of 20 physicists and graduate students, led by faculty at the California Institute of Technology (Caltech) in partnership with scientists at other universities in Austria, Germany, Canada, and USA. This theoretical and experimental research ("R1" on the R&D

[3] "Sharing of Data Leads to Progress on Alzheimer's", N.Y. Times, August 12, 2010.

continuum) in 'Optomechanics' (i.e. use of light to manipulate mechanical devices at nanoscale) was one part of a larger program sponsored by DARPA (Defense Advanced Research Projects Agency of the US Defense Department) to study "**O**ptical **R**adiation **C**ooling and **H**eating of **I**ntegrated **D**evices" (ORCHID). The DARPA program was organized in 2 time-critical 2-year phases—our study concentrated on the initial 2-year phase.

The closest collaboration in this project (see Figure 5) linked Caltech's Micro and Nano-Photonics Group and the Quantum Optics and Nanophysics Group at the University of Vienna, Austria. Within this arrangement, the Caltech lab engineered nanoscale objects (e.g. a tiny mechanical silicon beam) and conducted its own experiments, such that laser light of a carefully selected frequency could enter the nanoscale object and, once reflected, carry away thermal energy, thereby "cooling" the system. The Caltech lab also fabricated such devices for use in similar experiments run on significantly different equipment in the Austrian Quantum Optics laboratory. Thus, there was strong interdependence between the Caltech Group and the Austrian Group. However, up until the 'Orchid' project, staff from these two scientific groups had never collaborated and had met only briefly at conferences.

Figure 5: Collaborative Relationships in the Caltech 'Orchid' Project



The Vienna school has a world-famous reputation for its technical infrastructure enabling experiments at 1000 times lower temperatures than is possible at Caltech. However, the Austrian lab cannot make its own quality devices for experimentation, and thus depended upon the Caltech lab that can achieve state-of-the-art patterning of nanostructure devices.

Another set of participants involved with this experimental research was a team of three schools of Theoretical Physicists. The 'Theory' team was brought together for the 'Orchid' project at the initiative of the DARPA Program Manager who polled the Experimental scientists for recommendations of specific Groups of Theoretical Physicists most capable of providing "support for experimentation" and for advancement of optomechanical theory based on 'Orchid' experimental findings. Among the principal investigators on the 'Theory' team, only two members had done prior work together, and none had worked with the Austrian or Caltech Group.

4.3.1 Deliberations

A key deliberation topic that has recurred frequently during the Orchid project is the Selection of what Experiment(s) to run. This deliberation also illustrates the significance of collaboration between the perspectives of theoretical and experimental physics. In one instance, during a visit to Caltech, a graduate student associated with the German school of Theoretical Physics took note of experimental data that his Caltech colleagues had generated quite by chance and were inclined to discount as an "artifact". However, the German graduate student interpreted this data as indicative of an "interesting" optomechanical effect that had been predicted by Theoretical Physicists, although the same theory suggested it would be extremely difficult to achieve such an effect experimentally. Once Caltech physicists were informed and persuaded by this theoretical understanding, a new experiment was devised, and the predicted effects were then effectively demonstrated.

Among the Orchid project experimental scientists, many examples exist of joint participation in deliberations involved with the detailed Design of Experiments, both in terms of procedures and equipment design. The most complex deliberation involved the challenge of what and how to redesign a particular experiment in order to achieve a match between the wavelength characteristics of the optomechnical device fabricated at Caltech, and on the other hand, the wavelength of the light source to be utilized in running the experiment in the Austrian laboratory.

Interpretation of experimental Data has been another key deliberation. This deliberation has relied very much upon the differing perspectives of the two main Experimental Groups, as well as input from the perspective of Theoretical Physicists. Each discipline has also gained much from this collaboration that has both generated new theory and enriched experimentation. This is a type of deliberation that can continue over an extended period of time, with substantial lapses or 'incubation' time in between communications, and with various sub-topics, such as refinement of the data for eventual publication.

4.3.2 Knowledge Barriers

It has been established by a number of prior studies that "greater variety of work practices negatively impact performance" in virtual organizations (Chudoba et al., 2000). Here in the Orchid project, the two Experimentalist Groups, of Quantum Optics and of Nano-Photonics were based on related but very different disciplines, and used different language to describe similar data. An even more challenging difference was that the Austrian laboratory had never measured the types of optomechanical devices fabricated by the Caltech Group. Furthermore, within this project, the Theoretical Physicists also maintained their own approach to problem solving that differs from that of either of the Experimentalist schools.

Conversely, the wide geographic dispersion of scientists in this collaboration combined with the high level of 'reciprocal' and 'team' interdependence between their disciplines and laboratory facilities implied a constant threat of a failure to utilize knowledge, if the diversity of these scientific perspectives could not be accessed and integrated for precise moments of creative problem-solving and interpretation in the experimental process.

Between the two experimental laboratories, there was also a major barrier to the acquisition of knowledge, resulting from the difference and incompatibility in the equipment that the laboratories used for experimentation. It was an overall advantage for the Orchid project that the University of Vienna laboratory has a technical infrastructure that can do experiments at 1000 times lower temperatures than is possible at Caltech. However, the state-of-the-art techniques that Caltech had perfected for "getting light in and out of" its optomechanical devices would not work on the Austrian experimental infrastructure, unless some significant modifications were made.

Finally, all of these scientists in their different institutions were simultaneously very occupied with other research projects and priorities. The potential for a conflict in priorities or a failure to communicate was always present in this transcontinental, cross-time zone collaboration. The Orchid project may also have been particularly vulnerable to the effects of any failure to share knowledge because, although it was exploratory research, the project had to be conducted under very tight timelines with 6-month review periods administered by the funding agency, DARPA.

4.3.3 Coordination Mechanisms

For all of these reasons, members of the Orchid project anticipated that this project would be their most challenging experience yet in virtual R&D. Nevertheless, the overriding factor was their very strong "motivation" to collaborate. Between the leaders and staff of the two experimental laboratories, there was tremendous mutual respect. In the opinion of the Austrians, "no group worldwide can make such devices as at Caltech", and similarly, the view expressed by members of the Caltech Group was that the "Vienna school is world famous" for the quality of its experimental scientists and the capability of their equipment.

Members of the Orchid project who had experienced difficulties in other multi-university projects commented that it was significant that the relationship between the two experimental laboratories was "complementary" and not "competitive". Their respective expertise differed—the ability to engineer micro-optomechanical devices versus a quantum optical background and knowledge—but it was at the same time, "a perfect match". The combination of the two types of expertise created what the scientists perceived as a unique opportunity for breakthrough—in the words of the Austrian Group leader--"the first time in principle…to enter a regime that we can do [quantum] experiments with truly microscopic systems". This compelling 'mission' or goal encouraged members of the Orchid project to take personal initiative to overcome many barriers.

Nevertheless, this project involved a tremendous challenge to invent a new methodology so that Caltech devices could run on the different experimental equipment in the Austrian laboratory. Moreover, this co-invention required a detailed understanding by each party of the other's technical capabilities and limitations, a very challenging task within the setting of a virtual organization.

The mechanism that most helped to bridge these different frames of reference in the Orchid project was the role of an "embedded researcher"--a graduate student from the Austrian laboratory who came, very much by chance, to Caltech for a 5-week visit, just when the project was experiencing a delay in development of the optomechanical device and experimental design intended for use in the Austrian laboratory. In the words of the Austrian graduate student: "*it's very hard to really get on the same page and really understand what the other one means if you don't see…the design, see how the people work…I wasn't really aware of how different the experiments were [in Caltech] than in Vienna. And, we just had to merge those two different approaches together*."

Another experience of 'emergent' coordination occurred between the 'Theory' team and the Experimental Physicists. Partly, this coordination was planned and encouraged by the efforts of the DARPA Program Manager who was recognized by everyone in the Orchid project as having played a useful "facilitation" role, first by inviting Theorists onto the project team, and then, by administration of regular program review meetings.

Nevertheless, during most of the project, the 'Theory' team worked entirely at a distance from the Experimentalists, studying research reports and experimental data. However, "in terms of real [theoretical] research being conducted…the most impressive example" occurred when the leader of the German school of Theoretical Physics made an unanticipated intervention to send one of his graduate students to work for 5 consecutive months in the Micro and Nano-Photonics lab at Caltech. During this period, the graduate student (linked by almost daily Skype and Email communication with his German colleagues) was "able to give real-time suggestions to the Experimentalists on what they should be measuring", or to quickly interpret experimental data that "it would have taken [the Experimentalists] a long time to figure out".

During the remainder of the Orchid project, while back in Germany, the Theoretical Physics graduate student, now knowing much better the 'language' and the capabilities of the Caltech lab, performed an ongoing liaison role for the remainder of the project, 'translating' and expediting communication between Caltech and the multi-university 'Theory' team.

Most communication in the Orchid project occurred via Email, among the widely dispersed scientists and graduate students exchanging documents or experimental results without the expectation of instant response. After reflection and preparation, very often, the next step in the deliberation was one or more synchronous Skype conversations or teleconferences to discuss and make "sense" of the shared information. Sometimes, a "screen-sharing" feature was utilized to supplement this 'sense-making'. Transcontinental Skype calls could occur daily whenever the experimental process picked up intensity. Social media were also used, particularly by some of the graduate students, to supplement Email.

However, "timely" face-to-face (F2F) communication was considered to be vital "to sort out basic directions". F2F communication had to be "timely" and very selective because of the costs involved for such a geographically dispersed collaboration. Brief visits to one another's laboratory or joint participation at scientific workshops were the forums for informal communication and mutual adjustment that proved essential at critical points of convergence for the planning of experiments and the data refinement stages.

F2F communication also proved to be significant for building trust between the Caltech and European researchers whose Groups had never previously collaborated. For example, Caltech graduate students and their "embedded researcher" counterparts developed a "personal" friendship more than just a "professional" relationship. As a result, they became "more willing to have discussions when [they] don't have clear, conclusive ideas", and "more willing to share data that [they] don't understand"—in their words, they became "not as hesitant with each other", a critical factor in sharing and developing knowledge.

In other research collaborations, however, unplanned F2F visits by "embedded" graduate students or "timely" visits to refine data being generated in another Group's laboratory could have been viewed as an invasion. This was not the case in the Orchid project, where the principal investigators regarded each other as "extremely easy to work with", and as having an "intuitive" understanding of "the social aspects of collaborative projects".

Indeed, despite major social and technological challenges, (see Table 3), during the initial 2-year phase of the Orchid project, scientists at Caltech and their Austrian peers completed an intense period of experimentation that yielded a series of internationally recognized publications and "milestone" demonstrations of a capability for "quantum experiments that scientists have long dreamed of conducting"[4].

[4] News Release, California Institute of Technology, Pasadena CA, October 5, 2011.

Table 3: STS Analysis of 'Orchid' Project

Pure Fundamental Research (R1)

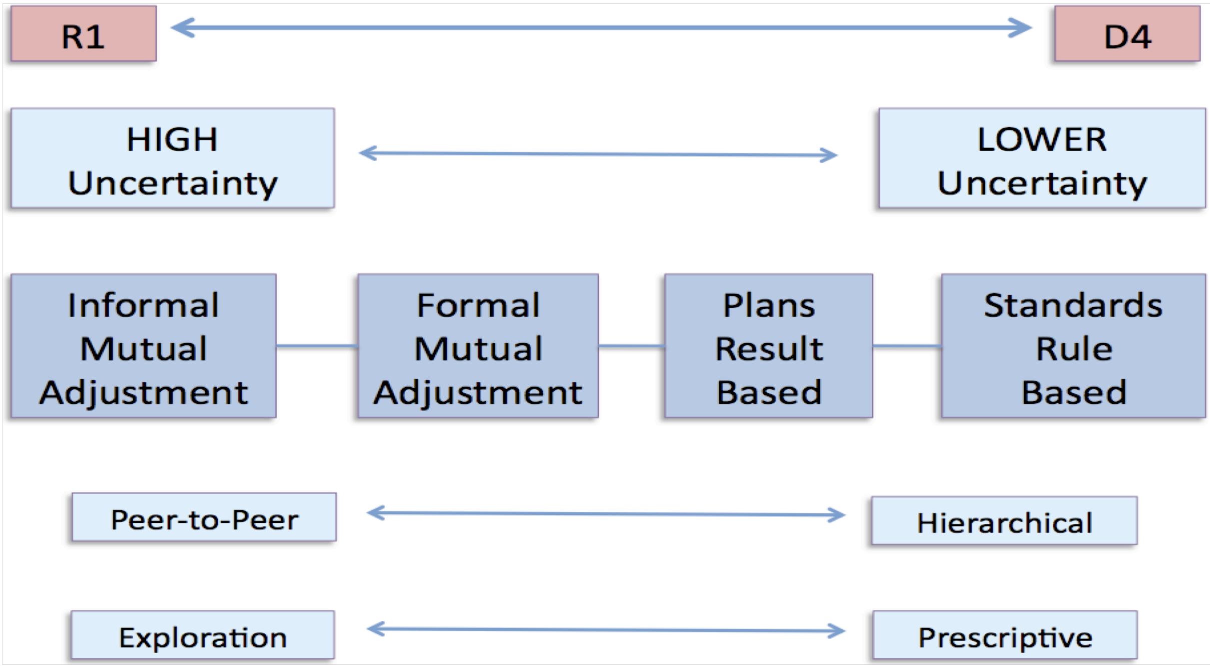
Key DELIBERATIONS	Knowledge Development BARRIERS	Significant COORDINATION Mechanisms
-Selection of what Experiments to run -Design of Experimentation -Interpretation and Refinement of Data	-Frame of Reference 'language' barriers between diverse scientific disciplines -Knowledge Acquisition barriers due to very different technology platforms -Failure to Access and Utilize diverse knowledge and perspectives in a timely and effective manner	-Compelling shared 'mission' -Liasion 'straddler' Role of "embedded researcher" -Facilitator/'System Integrator' Role of DARPA Program Manager -Formal semi-annual Project Review Meetings -Impromptu communication via Skype or IM -Timely Co-location/On-Site Visits or joint participation in Workshops, for specific F2F communication

5. SUMMARY AND DISCUSSION

While all four main categories of coordination (standards, plans, formal mutual adjustment, informal mutual adjustment) were utilized to some (even limited) degree within each of the three R&D projects in our study sample, a pattern emerges of different *types* of coordination mechanisms being predominant or primary in mitigating knowledge development barriers for different R&D stages.

Thus, these comparative case study findings and the concept of the R&D Continuum together with prior studies about "Uncertainty and Coordination in Global Software Projects" (Lai et al., 2003; Sabherwal, 2003) yield a model of coordination across the full continuum of the R&D process. This model extends prior theory to include the Research dimension, and specifically, Pure/Fundamental Research (R1). Furthermore, particularly in this study of R&D conducted in *virtual* organizational settings, the relationship found between different stages of R&D (with differing levels of task uncertainty) and corresponding types of predominant coordination mechanisms can be illustrated as in Figure 6 below.

Figure 6. Coordination across the Continuum of the R&D Process



Moreover, within these different types or categories of coordination, and specifically within a *virtual* organizational context for R&D, what is especially relevant for practitioners are the examples of specific mechanisms that our research findings suggest have been *most significant* in mitigating knowledge development barriers within each of the three *virtual* R&D projects in our study sample (see Table 4).

For example, at the more stable "implementation" stage of Scale-up Development (D4) for the 'Large Video Game' project, although collaboration with vendors has been supported by shared development tracking software and web-based project management tools, the category of coordination mechanism that project participants indicated had the strongest positive impact on managing performance appeared to be *standardization* (of output, skills, and processes).

Conversely, at the highest level of task uncertainty and equivocality, namely, Pure Research (R1), the 'Orchid' project scientists did rely upon standardized experimental procedures but said they gained the greatest value from coordination through *informal* mechanisms of impromptu communications and timely site visits for face-to-face interaction, as well as through more structured *formal* mechanisms such as the graduate student "embedded researcher" role and the "facilitation" role fulfilled by the project funding agency's program manager.

Table 4. *Most Significant* Coordination Mechanisms in Sample *Virtual* R&D Projects

Coordination Category	Case Examples	'Orchid'	'UDS'		'LVG'	
		R1	D2	D3-D4	D3	D4
Coordination by **STANDARDS**	•Output Standardization—prototype, screen shots, visual targets					+
	•Skills Standardization/training			+	+	+
	•Standardization of Processes					+
	•Diagnostic instruments			+		
	•Data formats			+		+
	•Error-tracking procedures					+
Coordination by **PLANS**	•Delivery schedules			+	+	
	•Project milestones			+	+	
	•Requirement specifications			+	+	
	•Sign-offs				+	
	•Financial incentives			+		
	•Compelling 'mission'/goal	+	+			
Coordination by **FORMAL MUTUAL ADJUSTMENT**	•Site inspection/verification				+	+
	•Hierarchy/vertical communication				+	
	•Shared database/repository					
	•Formal meetings/status review	+	+		+	
	•Steering committees/task force		+			
	•Referent organization		+			
	•Facilitator/'Network Builder' role	+	+			
	•Liaison/'Straddler' role	+			+	
Coordination by **INFORMAL MUTUAL ADJUSTMENT**	•Impromptu communication	+	+			
	•Informal meetings	+	+			
	•Conferences, workshops	+	+			
	•Site visits	+				
	•Temporary co-location	+				

Key: + Designates Active & Significant Coordination Mechanism in a specific virtual R&D Project

Furthermore, STS analysis of specific deliberations provides additional insight as to why the categories of key coordination mechanisms differ in different stages of R&D. For example, in Pure Research (R1), judgments by 'Orchid' project scientists from different disciplines about what experiments to run, or in the case of Exploratory Development (D2) for the multidisciplinary, multi-party negotiations among Alzheimer Disease Centers about the elements to include in the UDS, both R&D projects have required "sense-making" (Weick, 1995) and building understanding, more than the data-sharing that has been critical for deliberations in more structured Start-up (D3) and Scale-up (D4) Development work. Key deliberations in work at the R1 and D2 stages have required structural mechanisms with a strong capacity to resolve equivocality, more so than simply to reduce uncertainty due to lack of information.

This finding reinforces the value of a k*nowledge-based* perspective in addition to an *information-processing* perspective of coordination for R&D work (McDermott, 1999). As stated by Kotlarsky et al. (2008), a focus on information processing applies well in "task environments where knowledge requirements are well known", whereas a knowledge-based perspective "focuses on individuals' *understandings* and how they interrelate" for processes of integrating and creating knowledge.

Our comparative case study also links task coordination theory developed in the context of co-located work, with the experience of R&D projects in distributed, virtual work. There are of course many similarities between virtual and co-located R&D. However, as found by Gassmann and von Zedtwitz (2003) in their empirical studies of numerous transnational R&D project organizations, and by Sutanto et al. (2011) in their study of global virtual teams, there are indications in this comparative study that virtual R&D projects require augmented or strengthened coordination mechanisms, as compared with similar co-located work. As Herbsleb (2007) states: "the fundamental problem of global software development is that many of the mechanisms that function to coordinate work in a co-located setting are absent or disrupted in a distributed project".

In our study sample of R&D projects, a number of participants reported that, compared to their experience of co-located work, some potential barriers to the sharing of knowledge (e.g. intellectual property issues, divergent values and priorities) were more difficult to manage within a virtual organization of R&D (as compared with co-located research or development).

For example, participants in the 'LVG' project involving "D3" start-up type development work reported that the issues associated with unclear expectations or estimation of project scope would have been corrected fairly quickly through informal communications between supervisors and internal staff in their prior experience of co-located work. However, when working with 'far-flung' external vendors, effective coordination required more detailed scheduling and "chunking" of projects into phases that could be more closely monitored by a new "product owner", single point of contact role within LVG Inc.

Similarly, previous studies of co-located R&D projects (Purser et al., 1992; Shrivastava, 1983) have concluded, "technically complex and highly non-routine projects are more likely to succeed in a participative learning system" with "more loosely structured deliberation forums" (Purser, 1990). However, as is the case with many virtual organization settings where there are multiple organizations with diverse interests, the case in our study sample of "D2" advanced development of the Uniform Data Set required something more than "participative management". In this case, UDS was significantly advantaged over its predecessor (minimal data set) by creation of a National Alzheimer's Coordinating Center (NACC), a "referent organization" role (Trist, 1983), separate from any operating agency, but guiding and enabling self-regulation of this complex development project by the scientists and staff from the network of 29 Alzheimer's Disease Centers.

The ‘Orchid’ project highlighted another heightened challenge of virtuality, especially for the more exploratory stages of R&D with greater degrees of equivocality. As Gassmann et al. (2003) found, “if knowledge is to be exchanged across large distances, the distinction between tacit and explicit knowledge becomes even more important…tacit knowledge is difficult to communicate” (see also Nonaka and Takeuchi, 1995). In fact, the different frames of reference held by ‘Orchid’ project scientists from different disciplines and from different experimental laboratory experience created some significant barriers to sharing and integrating knowledge.

Fortunately, what was discovered serendipitously and contrary to “normal” practice, by leaders of both the experimental and theoretical scientific groups was the value of deploying one or more graduate students for extended periods of time as researchers temporarily “embedded” in one another’s institutional setting and work practices. During and after their stay “abroad”, these “embedded researchers” contributed vital translation and liaison across disciplines and institutions. Their function resembled the “semiotic broker” role for “perspective making and perspective taking” in communities of knowing (Boland and Tenkasi, 1995). As a formal adjustment coordination mechanism for global software development, this has also been described as the “straddler” role (Heeks et al., 2001; Lai et al., 2003), acting as a conduit “for transfer of tacit knowledge”.

In their inter-organizational communication, however, the Orchid project scientists did rely most of the time upon electronic media for coordination of their theoretical or experimental research. Their use of Email followed by Skype teleconferences replicated the pattern suggested by “media synchronicity theory” (Dennis and Valacich, 1999). Also, these scientists and their graduate students used or were familiar with virtual workspace IT tools for task coordination (Malhotra and Majchrzak, 2012), such as instant messaging, electronic whiteboards, video conferencing, and network databases.

However, even for the millennial generation graduate students who felt more affinity with some of these media, “timely” face-to-face (F2F) contact, (by comparison to IT-mediated communication), was seen to provide vital “intensity and spontaneity” at key moments when people needed to converge and coordinate on fundamentally “new ideas, new directions”. In the words of the ‘Orchid’ project scientists, “teleconferences don’t happen by chance”, and yet, in fundamental science, “there’s this random chance occurrence of ideas…you chat about a lot of different topics, and then, somehow, the germ of a new idea comes up”. Without opportunities for F2F communication, “eureka moments won’t happen”. Along with this spontaneity, there needs also to be the “intensity of constant exchange” because in “generating new ideas, you always have an incubation time”.

In both the ‘Orchid’ and ‘UDS’ projects, periodic F2F communication (in site visits, workshops, conferences, etc.) was a mechanism that also enabled trust building, a key part of “the underlying foundation of knowledge creation and virtual teams” (Wipawayangkool, 2009). Similar to the view of McAllister (1995) that trust is cognitive and affective-based, ‘Orchid’ and ‘UDS’ project scientists developed “professional” and “personal” relationships.

What also contributed to the relationship quality (including trust) in both of these highly innovative projects (involving diverse and sometimes competitive organizations) was a compelling shared purpose. For the widely dispersed 'Orchid' project team members in Europe and North America, who had experienced other multi-university projects (where "many groups that were very loosely connected in their topics…decided to band together to get a grant…[as] a nice research network on paper"), this specific collaboration was uniquely "focused on one topic of vital interest to all the scientific groups". The project was seen as a "big advantage"— to achieve together a "scientific breakthrough".

Although difficult to establish in a virtual organization (Blackburn, Furst and Rosen, 2003), shared values and mission support members' "need to feel a sense of community in virtual organizations" (Carroll and Wang, 2011). Shared purpose or strategic vision may function in a virtual organization like a high level form of planned targets and goals, identified by Galbraith (1974) as a basic mechanism of coordination. In his discussion of coordination mechanisms within the future of organization design, Galbraith (2012) comments on the "emphasis that is placed on developing shared values that guide decisions without communication between interdependent units and managers".

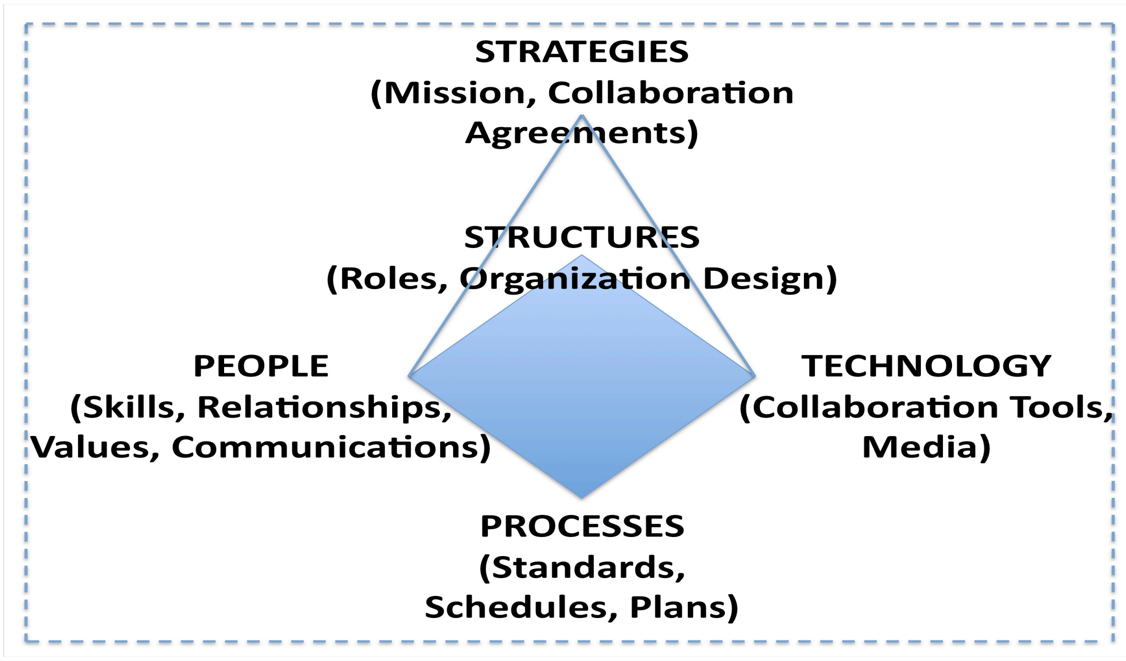
Across the organizational boundaries in the 'Orchid' project, it is apparent that the effective use of periodic F2F communication was based upon a unique set of collaboration values and skills shared by key leaders in the team's various scientific groups. Similarly, the NACC as a coordination mechanism for the 'UDS' project has been made particularly effective through leadership's use of unique "reticulist" (Power, 1973) or "network builder" skills (Hargadon, 2003). These skills involve a dual capability—"to appreciate the complexity of political and organizational relationships…[and] the ever-shifting structural relationships among substantive issues…[in an inter-organizational planning process]" (Friend, 1997).

Indeed, in each of these virtual R&D projects, effective coordination has involved a specific combination of elements and mechanisms. This is consistent with a "knowledge-based" model of coordination applied earlier to a study of global software projects (Kotlarsky et al., 2008) where different types of coordination mechanisms were found to make different contributions to knowledge sharing and development--*organizational/structural mechanisms* facilitate knowledge flows; *work-process mechanisms* make knowledge and expectations explicit; *technology-based mechanisms* amplify knowledge; and, the *inter-personal skills and mechanisms associated with people* build social capital.

Finally, including *strategic mechanisms* that define common purpose for knowledge collaboration, (as suggested by the experience of our sample of case studies) yields a framework for coordination of distributed R&D work, that reflects the thinking of the National Science Foundation VOSS program[5]; namely, these Virtual Organizations are, and need to be coordinated as, open Sociotechnical Systems (see Figure 7).

[5] NSF Program Title: Virtual Organizations as Sociotechnical Systems (VOSS)

Figure 7: Sociotechnical Systems Framework for Coordination of Virtual R&D



As Binder (2008) and Cummings (2007) have contended, there is a "cost to overcome" with global projects and multi-university research, and a key driver of that cost is coordination. Even though there is "a common notion that collaboration technology and bandwidth will [alone] allow a virtual team to perform as if co-located…evidence shows this notion to be a naïve myth" (Moser and Halpin, 2009). One implication for practitioners, from this comparative study of virtual R&D is that "third generation" STS methodology (updated for non-routine work in a virtual context) provides a way to utilize elements of *both* social *and* technical sub-systems to assess and overcome "coordination costs".

Locating one's work on the R&D continuum can help practitioners to anticipate the general degree of their coordination challenge and the type of coordination mechanisms that are likely to be most important. Then, STS analysis of deliberations and knowledge development barriers can provide detailed insights to inform the project-specific design of coordination for virtual R&D.

STS design of coordination and deliberations for virtual organization "is not a mechanical extrapolation from prior analysis…it is a creative synthesis informed by that analysis" (Pava, 1983). Nevertheless, the elements that are the ingredients for the options of 'when', 'where' and 'how' to effectively coordinate work such as virtual R&D can be mixed and matched from the palette of a sociotechnical systems (STS) framework (Figure 7).

With this understanding of STS design, planning and budgetary provision for coordination can contribute to the success of R&D projects that are increasingly conducted in a virtual organizational context such as multi-university research or global technology consortia.

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