Interdisciplinary Interactions During R&D and Early Design of Large Engineered Systems

by

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Dedication

This research is dedicated to Jesus Christ.

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Abstract

Designing Large-Scale Complex Engineered Systems (LaCES) such as aircraft and submarines requires the input of thousands of engineers and scientists whose work is proximate in neither time nor space. Comprehensive knowledge of the system is dispersed among specialists whose expertise is in typically one system component or discipline. This study examined the interactive work practices among such specialists seeking to improve engineering practice through a rigorous and theoretical understanding of current practice. This research explored current interdisciplinary practices and perspectives during R&D and early LaCES design and identified why these practices and perspectives prevail and persist. The research design consisted of a three-fold, integrative approach that combined an open-ended survey, semi-structured interviews, and ethnography. Significant empirical data from experienced engineers and scientists in a large engineering organization were obtained and integrated with theories from organization science and engineering. Qualitative analysis was used to obtain a holistic, contextualized understanding.

The over-arching finding is that issues related to cognition, organization, and social interrelations mostly dominate interactions across disciplines. Engineering issues, such as the integration of hardware or physics-based models, are not as significant. For example, organization culture is an important underlying factor that guided researchers more toward individual sovereignty over cross-disciplinarity. The organization structure and the engineered system architecture also serve as constraints to the engineering work. Many differences in work practices were observed, including frequency and depth of interactions, definition or co-construction of requirements, clarity or creation of the system architecture, work group proximity, and cognitive challenges. Practitioners are often unaware of these differences resulting in confusion and incorrect assumptions regarding work expectations. Cognitively, the enactment and co-construction of knowledge are the fundamental tasks of the interdisciplinary interactions. Distributed and collective cognition represent most of the efforts. Argument, ignorance, learning, and creativity are interrelated aspects of the interactions that cause discomfort

but yield benefits such as problem mitigation, broader understanding, and improved system design and performance. The quality and quantity of social interrelations are central to all work across disciplines with reciprocity, respectful engagement, and heedful interrelations being significant to the effectiveness of the engineering and scientific work.

Chapter 1: Introduction

Problem Statement

The Apollo missions, the Hoover Dam, an aircraft carrier, a nuclear-powered submarine, a Boeing 747 aircraft – all of these inspire and to some extent mystify us. How do they do it? Did the numerous engineers and scientists who labored over equations and queried in laboratories for many years actually "see" the enormity of the ultimate system they helped create? Perhaps a more apt question is: How *could* they see it?

When complete, these large-scale engineering feats rest on the ingenuity of thousands of engineers and scientists whose work is proximate in neither space nor time. They endeavor in varied laboratories that dot the country, and sometimes the globe, and their work spans years that frequently stretch into decades. The researchers and developers of the technologies upon which the system design rests never convene. Their work and their wisdom are knit together to shape the early conceptual design of systems whose scale is too grand for any one person or small group of people to fully comprehend. The effective early "designer" of a large-scale, complex engineered system (LaCES) is a dispersed team of thousands of researchers that never convenes. The present research is a study of the interactions of that dispersed team.

The field of inquiry in which I situate this work is the study of engineering practice from research through early conceptual design of very large, complex engineered systems such as aircraft, submarines, and nuclear power plants. I sought to better understand the earliest design phase of LaCES. How do engineers and scientists interact — across different technical domains, from different departments or geographic sites — in research and development (R&D)? How might these interactions lay the groundwork for the subsequent design of large systems? Is there an intellectual interdependency from distributed R&D efforts upon which we rely in systems design, but which we do not fully understand? To answer these questions, this study focused on understanding *how* engineers and scientists interact across different technical domains

and *why they do so* in a particular manner, with a concentration on recognizing some of the precursors of system design for large engineered systems.

This work makes a new intervention in an interdisciplinary field that joins engineering, organization science, and psychology; for it endeavors toward providing a integrated analysis that synthesizes three constructs: 1) engineering practices of interdisciplinary interactions in R&D and early design of LaCES; 2) where these practices take place within a sizable, dispersed organization; and 3) including individual cognition and expertise from a great many participants in LaCES design. An analysis of empirical data of engineering practice from experienced practitioners in these three areas is used to improve understanding of some of the design precursors for LaCES.

The goal of this work is not prescriptive in nature but rather descriptive, seeking to advance engineering practice by improving our understanding of current practice. This is accomplished by providing deep descriptions of the related engineering and organizational practices and deriving explanatory integrative frameworks and conceptualizations that enable a more theoretical analysis of these practices. Enhanced understanding of existing practices can be transferred to many engineering contexts, offering a foundation from which future improvements to practice may be defined. The ultimate motivation is to better understand how to harness the collective wisdom of the large-scale human system that underlies engineering system design. This extensively trained human system, of diverse scientists and engineers, holds a repository of capabilities that are yet to be fully tapped. What might we enable through innovative system design in engineering if we better understand how to harness combined engineering intellect?

Research Questions

This study focuses on understanding the interactions between large numbers of engineers and scientists from different disciplines during the R&D and early conceptual design phases of developing large engineered systems such as aerospace systems. To facilitate a holistic understanding of the research topic, an interdisciplinary perspective informed by engineering practice as well as theoretical foundations from organization science and psychology was adopted.

This study delves into the interdependence of the engineering disciplines and the associated non-hierarchical interactive practices between researchers (depicted in the dotted lines in Figure 1). Rather than focusing on hierarchical practices (depicted in the solid lines) and connecting mathematical models and hardware, this work focuses instead on human-to-human interactions between disciplines and on the perspectives that drive these interactions, posing the following research questions:

1) What are current practices in and perspectives on interdisciplinary interactions during research and development and early conceptual design of large engineered systems?

2) Why might these practices and perspectives prevail and persist?
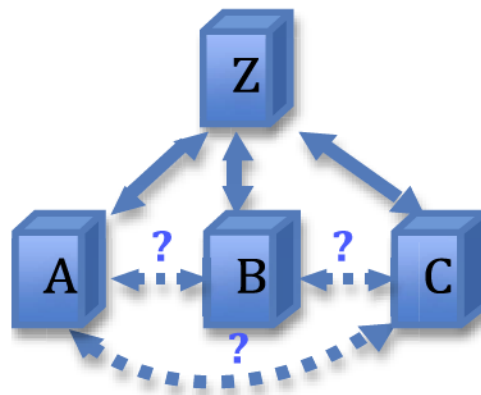
Figure 1 Cross-Disciplinary Interactions

With an effort to improve understanding of current engineering practice, data were gathered from practitioners in large engineering organizations through a multi-method approach of surveys, interviews, and ethnography. The data were synthesized with relevant aspects of existing theories to derive integrative frameworks and explanatory conceptualizations that provide a more theoretical and holistic analysis of existing practice.

Discussion is limited to the human-to-human interactions between researchers from different disciplines as the unit of analysis. Not analyzed here are engineering education, professional training, mathematical model and hardware integration, and factors external to the research, development and early design phases of the

development of large engineered systems. Rather, analysis is concentrated on the study of the human interactive connections of large, dispersed organizations of engineers and scientists whose work is intangibly connected to a system design that is in its earliest stages of development.

The research questions seek to reveal how these connections are made and why, with an overarching goal of understanding how the connections impact subsequent system design. Ultimately, this work seeks to advance the science of designing large engineered systems by improving understanding of some of its precursors.

Importance and Contribution of this Work

The major contributions of this dissertation are 1) Obtaining extensive and rare empirical data on the work practices and perspectives of experienced LaCES practitioners through surveys and personal interviews; and 2) analyzing this data using several theories from social science and interpreting the analysis results in an engineering context. This data and integrative analysis enable an improved understanding and clarification of interdisciplinary practice in R&D and early design of LaCES based on data from actual engineering practices versus simulation. This enhanced understanding can provide a rubric to clarify work practices and organizational communication potentially reducing confusion and improving efficiencies. Additionally, while it is common to refute theory with data from practice, this study refutes assumptions regarding practice with data of actual practice. For example, the common assumptions held by engineers that organization structure and aspects of social capital are insignificant in engineering R&D are refuted. Ultimately, this study provides an improved understanding of the practice of engineering using relevant data and fusing different social science theories. This improved interdisciplinary understanding can provide a rigorous basis for identifying practical improvements to engineering and broadening our understanding of the applicability of social science theory.

An improved understanding of engineering and cognitive interdependencies during R&D and early design of large systems can provide several benefits toward enabling greater system performance and reduced development time and cost by: 1)

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reducing mistakes that often occur between knowledge bases; 2) improving awareness of interactions between technologies and components in a system; 3) increasing creativity and innovation, both of which are heightened with diversity of thought; and 4) improving utilization of existing intellectual, physical, and social capital. These benefits may lead to systems with increased resilience, fewer defects, and new disruptive abilities, while improving efficiencies in system development and design.

Background

Our planet increasingly relies upon large-scale engineered systems for many of its basic operations; from systems that supply energy such as electric power grids and water, to systems that transport people and goods such as aircraft and cargo ships. These systems are no longer solely applicable to industrialized nations, but are also employed to connect and supply small villages with satellites, cell phones, and medicines. In the West, we have grown accustomed to the benefits of our large systems and often over-look their influence on our way of life. Before leaving for work, many Americans take advantage of the capabilities of a weather satellite, a cell phone tower, a fiber optic network, a water supply system, an electric power grid, and use products shipped by a network of aircraft, trucks, and ships.

Labeled Large-Scale Complex Engineered Systems (LaCES) in this document, these systems uniquely comprise a blend of extremes in terms of physical size, technical and financial risks, organizations, and collateral impact. LaCES include aerospace (e.g., aircraft, space systems), large maritime (e.g., submarines, aircraft carriers), nuclear (e.g., power plants), and major civil infrastructure systems (e.g., water supply systems, electric power grids, offshore oilrigs, and air and ground transportation systems). The science of designing LaCES is being pressed to evolve to address growing demands in many areas including: national defense, environmental sustainability, population growth, and global corporate operations. The important role of LaCES in societies around the globe is one inspiring motivator for this work.

Yet, system design of LaCES is met with significant challenges. The design process is very costly (tens of millions to billions of dollars for one system); is lengthy

(often requiring more than a decade to develop one system); is interdependent with many other systems (such as public policies and environmental issues); and is not comprehensively understood. A major concern for many governments is escalating time and costs required to develop systems – both of which are rising at a rate that is unsustainable.[1] The prolonged time required to develop LaCES makes it problematic to address interoperability with other technologies and systems that change more rapidly such as telecommunications. Further, the arduous size of the system and organizations needed to develop them strain many existing engineering design processes that were developed for smaller working scenarios and simpler systems. While several system design processes exist, many of these evolved over time rather than being rigorously created and fully understood.[1, 2]

Given these challenges, understanding and improving design for large systems has become imperative in the engineering community, with research programs burgeoning in many institutions. The emphasis for the current research effort is driven by two interrelated challenges and opportunities in systems design and development: 1) addressing engineering interdependencies, most of which may be first identified during the R&D and early conceptual design phases of development; and 2) addressing cognitive interdependencies in large, dispersed organizations of diversely trained engineers and scientists that research, develop, and design systems. As it is impossible to effectively solve problems that are insufficiently understood, this study seeks to investigate and understand current work practices in operational engineering laboratories that research, develop, and design LaCES in order to provide a more rigorous basis for exploring improved practices for innovative system designs of the future.

Most interesting from a personal perspective is the opportunity to understand how to better utilize untapped human potential and unused innovations that are latent in the R&D and early design phases but often insufficiently connected to be effectively used in later design phases. My motivation is to explore engineering and cognitive interdependencies by understanding interdisciplinary interactions during R&D and early design to better understand how to harness the collective wisdom of the large-scale human system that holds the engineering blueprints of future LaCES. I believe when

we can better exploit our God-given intellect, we open the doors to designs yet to be envisioned.

Context of the Research Study

In this section a brief summary of the context of this work is provided as an introduction. A literature review of each of the relevant domains of research is provided in the next section.

Summary of Research Context

The context of this work is determined by several characteristics of the engineered system and the organization that conducts R&D and early design. The enormity and complexity of the engineered system indicate that the early design effort is not led by a single designer or small group of designers who comprehend the entire system design and are able to delineate the interdependencies in the work of the respective engineers and scientists. Rather, "the sheer complexity of many design artifacts means that no one person is capable of keeping the whole design in his/her head and centralized control of the design decisions becomes impractical, so the design process is dominated by concurrent local activities."[3] From a sensemaking perspective Weick writes: "Portions of the envisaged system are known to all, but all of it is known to none."[4]

Hence in this study, the focus is not toward a single designer or a design group, but rather toward understanding how dispersed researchers interact to enable a potential future system design. While there are several well-utilized system design methods that integrate R&D results, such as Multidisciplinary Design Optimization (MDO) and Quality Function Deployment (QFD), etc., this study focuses on the human-to-human interactions during R&D and early design that are augmentative to these and other computer-based methods. Typically for LaCES R&D and early design, hundreds to thousands are employed at several different geographic locations. The size and geographic dispersion of typical R&D organizations oblige a focus on organizations and networks of people over a focus on individuals and teams, with an appreciation that the

latter creates the former.

Thus, this study examines organization science theories related to connections in organizations, such as distributed and collective cognition, social network analysis, and social capital.   The literature and theories on interdisciplinarity and connections across disciplines provided insight on knowledge integration across domains of study.   In engineering, the literature from system science, complexity science, system engineering, MDO, and system design informed the research.   The research design was grounded in qualitative methods.   As such, literature on methods in field studies in social psychology and organizations were extensively used, including topics related to: surveys, interviewing, observations, ethnography, and grounded theory.

While this study examines interdependencies in engineering and cognition during R&D in organizations and engineered systems that are both very large, it also examines the related theories in the literature associated with the research topic.   Ultimately, this study is a fusion of many different research genres.   This fusion is essential for enabling a more holistic analysis of the engineering practices studied.   Studying and fusing the diverse genres of literature to aid analysis in this study also makes it clear that there is a wealth of literature that is yet to be connected that may be useful for further improving engineering system design.

Clarification of Cross-Disciplinary Terms

In this section, literature on cross-disciplinary research is reviewed to clarify key terms that will be used in this work.   The original intent of this study is to focus on interdisciplinary interactions; however, a very early finding was that most respondents confused multidisciplinarity with interdisciplinarity in their descriptions and many were not familiar with what trans-disciplinarity referred to.   For example, a senior manager of a large self-titled "multidiscipline group" at a LaCES organization, who has extensive experience in MDO, queried: *"We have already included interdisciplinary aspects in our work – it is really the same as multidisciplinary.   Is there really a need to use a different term?"*

Similarly, respondents expressed many different views and related practices regarding what constituted "working across disciplines."   In analyzing the wide variety of

responses, it became clear that many respondents were actually referring to very different connotations of "working across disciplines" and, correspondingly, they were implementing many, very different practices.   These differing approaches and perspectives likely added to the organizational confusion and frustration related to working across disciplines that was apparent in the responses obtained throughout this research.

While definitions of working across disciplines are equivocal in many research articles, literature that focuses on interdisciplinary research is more concise and consistent. The following definitions are derived based upon several references.[5-16] Klein's caution on any taxonomy is also warranted: "Taxonomies construct the ways in which we organize knowledge and education. However, they are neither permanent nor complete and their boundaries change."[17]   The definitions that follow will be used consistently throughout this document.

Cross-disciplinarity: Used to indicated all types of interactions between disciplines in this document.

Multidisciplinarity: In a most rudimentary sense multidisciplinary simply implies the inclusion of multiple disciplines. In a more active sense, multidisciplinarity refers to the combination of multiple disciplines (which may be non-integrative), where each discipline preserves its methodologies and assumptions without significant modification from other disciplines.

Some insights from literature are useful. Based upon the definition developed by the Organization for Economic Cooperation and Development (OECD), Klein defines multidisciplinarity as *"an approach that juxtaposes disciplines. Juxtaposition fosters wider knowledge, information, and methods.   Yet, disciplines remain separate, disciplinary elements retain their original identity, any existing structure of knowledge is not questioned."[17]* For example, in a multidisciplinary context, different disciplines can be taken into account without active cooperation from the different disciplines. Interestingly, one researcher cites an illustrative example of this as "the engineering profession's effort to include social contexts of practice."[17]

Klein also describes an example of multidisciplinarity as when results of different disciplines are integrated into a common framework. This is a common practice in engineering in some forms of MDO and systems engineering. Repko notes that: "multidisciplinary approaches tend to be dominated by the method and theory preferred by the home discipline."[6] Quoting a definition provided by the National Academies, Repko describes multidisciplinary research as involving "more than a single discipline in which each discipline makes a separate contribution."[6]

While multidisciplinarity and interdisciplinarity both seek to overcome disciplinary monism, they approach this goal by different means.[6] Multidisciplinarity is distinguished from interdisciplinarity to account for the relationship *between* the disciplines. In a multidisciplinary scenario, the relationship between disciplines "may be mutual and cumulative but not interactive."[16] Klein writes: "when integration and interaction become proactive, the line between multidisciplinarity and interdisciplinarity is crossed."[17] In an interdisciplinary relationship, the practices and conventions of each discipline are interactively blended. Repko simplifies the delineation between multidisciplinarity and interdisciplinarity by comparing multidisciplinarity to a bowl of fruit and interdisciplinarity to a fruit smoothie. In the latter, the process of blending changes the contribution of each fruit, and in parallel, the process of integration changes disciplinary insight.[6]

Interdisciplinarity: The root prefix "inter," means "between."[18] Interdisciplinarity refers to the fusing and integrating of several disciplines, where *each discipline's methodologies or assumptions are interdependent on other disciplines.* This is a departure from the multidisciplinary approach where each discipline considers the perspective of another discipline or multiple disciplines are incorporated into one model. In interdisciplinarity, the practices and conventions of each discipline are *interactively* blended such that the disciplines are changed during the integrative process.

Repko notes "interdisciplinarity studies a complex problem (including mega ones) by drawing on disciplinary insights (and sometimes stakeholders views) and integrating them. By employing a research process that subsumes the methods of the relevant disciplines, interdisciplinary work does not privilege any particular disciplinary method or

theory." Rather, interdisciplinary research is usually undertaken to advance knowledge that lies beyond any one discipline, yet can still be very focused. "Understood as knowledge integration, interdisciplinarity is not the opposite of specialization. Research can be specialized (i.e., focused on a narrow topic) either within a disciplinary framework or drawing on various disciplines." ([Rafols & Meyer, forthcoming] from [5])

Perhaps the most salient discriminator for interdisciplinarity (as compared to multidisciplinarity) is that the individual disciplines are transformed during the integrative process and are no longer individually and distinctly distinguishable. For example, Klein notes "individuals may find their original disciplinary methods and theoretical concepts modified as a result of cooperation, fostering new conceptual categories and methodological unification (Boden 1999, pp. 19-22)."[17] At the greatest level of interdisciplinarity, the core issues and questions of a complex problem may "lack a compelling disciplinary basis, and a critique of disciplinary understanding is often implied. (Lattuca 2001, p. 117)"[17]

In multidisciplinarity, many different components may be brought together to create a new, engineered system by comprehensively including all factors from the individual components but without appreciably modifying each individual component – each component is still very distinguishable in the integrated system. In interdisciplinarity, many different components are blended together to create a new, engineered system by an iterative and reciprocal interplay between the components – changing each component in the process. The system developed by multidisciplinary means likely will be very different from the system developed by interdisciplinary means.

For example, consider two types of aircraft configurations shown in Figure 2. In a very general sense, some aspects of the major components of an airplane that is a conventional "tube with wings" could be developed through multidisciplinary approaches because major components such as wing, engine, and fuselage are physically connected and certainly coupled, but in a manner that allows the wing, engine, and fuselage to be developed somewhat separately, yet with consideration for connections and coupling. The different components remain distinct in the final system. In a general sense, a hypersonic air vehicle has a wing, engine, and fuselage that are so physically

enmeshed and coupled that much of the development of this type of vehicle will likely require more interdisciplinary approaches.
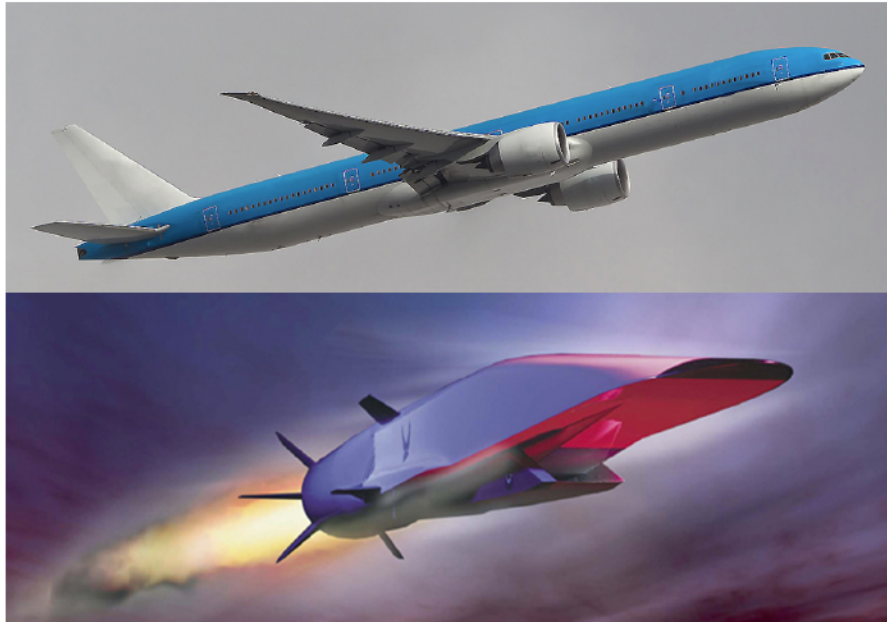
Figure 2 Example Large-Scale Systems

Transdisciplinarity: The root "trans," means to go across or beyond.[18] Transdisciplinarity describes cross-disciplinary scenarios when, during the integrative process, new disciplines emerge and transcend the constructs of existing disciplines. In this process, new practices and conventions are interactively created that transcend the practices and conventions of the original disciplines.

Examples of the above terms in engineering are:
- Multidiscipline: Combining a separately developed structural model with an aerodynamic model being mindful of boundary conditions, etc.
- Interdiscipline: Aeroelasticity, which is a study where structural models and aerodynamic models are interactively developed such that each model is a dynamic function of the other. A catastrophic coalescence of the two models is known as flutter.

- <u>Transdiscipline:</u> Creating an energy harvesting flutter concept. This concept transcends the interdisciplinary development of modeling the catastrophic event of flutter to exploiting the predictable, nonlinear event for energy harvesting purposes. Human learning is a quintessential transdiscipline effort for we combine disparate concepts and take them to a new state that may be inspired by but far removed from the original concepts.
- <u>Cross-discipline:</u> All of the above

This research effort is particularly focused on interdisciplinary interactions, as they offer a richer palette of study; however, an examination of the practices and perspectives of interdisciplinarity inherently involved exploring all forms of working across disciplines. Thus, in this report, the term cross-discipline is used most frequently, as it captures all forms of working across disciplines. The other terms are used as appropriate throughout the text.

Literature Review

This research study draws from several genres of literature. Literature from the following principal domains of research were reviewed in developing this effort: engineering design, MDO, systems engineering, complexity, systems science, sensemaking, social networks, social capital, creativity, positive organizational scholarship, distributed and collective cognition, and interdisciplinarity. A summary of some of these topics with exemplars is provided below.

I present this review prior to a description of the research methodology that appears in the next chapter. The three-pronged qualitative research methodology that is used in this study was developed based upon the insights from the different genres of research described below. The research methodology involved using a survey, semi-structured interviews, and ethnography. Throughout data collection and analysis, the literature was re-reviewed to identify connections between empirical data and existing theories. As such, I will identify a few examples from the empirical data in this literature review as examples of the integration between theory, research methodology, and

empirical data. These three constructs drove the research design and data analysis that evolved throughout this research effort.

In recent years, the challenges of designing LaCES have given rise to several scientific workshops, identifying new directions in engineering and social science research.[19],[20],[21],[22],[23],[24] A growing body of literature has begun to address the multi-faceted nature of LaCES where non-engineering influences can have significant impacts.[2, 3, 20-23, 25-36] For example, Ben-Ari discusses the heavy influence of government policies and contracting in the development of LaCES.[23] Stevens creates a framework that depicts the dynamics of different contexts of LaCES development incorporating system, stakeholder, strategic, and implementation contexts.[25] And, Wymore discusses numerous organizational and social aspects of systems engineering.[37] Much of the research on the design of LaCES has necessarily focused on addressing needs in systems engineering,[2, 31] MDO,[26, 33] and the social dimensions of system design practices such as decision and game theories.[32, 35, 38-40] This genre of design engineering research considers a broad definition of design to incorporate all of the influencing engineering efforts, from research through final system testing.

The current study focuses on the earliest stages of system design: R&D and early conceptual design. During these phases, hardware integration is typically on components of LaCES rather than the entire system. Some researchers often work alone or in small teams while many others work in large, dispersed teams with multiple organizational entities including large contractors, small businesses, universities, and government laboratories. Even for researchers that work alone largely, the broader, diverse, and dispersed team of researchers is intangibly linked by their focus on a subsequent system design.

At these early stages, it is unclear which of the many different technologies being researched and developed will be interconnected in the final system. Notional system architectures or configurations are often used as baselines and preliminary requirements are often provided to researchers to increase the relevance of their work. While it appears that an obvious means of connecting the various technologies and the respective researchers is via MDO methods which are commonly used to connect

different disciplines in a physics-based, software intensive approach, during this study I endeavored to ask a more open question: 'how do researchers of different disciplines interact?' – allowing the respondents to divulge their work practices without constraining analysis to MDO or other assumed methods of integration. This approach is consistent with an inductive, grounded theory approach used in qualitative analysis as described in the next chapter on research methodology.

In seeking the rationale and thinking behind many human-to-human interactive practices, the theories from complexity and systems science provided much insight.[3, 24, 25, 27, 28, 36, 41-45] These theories provide an approach to understanding systems that is decidedly different from the majority of existing engineering methods and engineering culture. Instead of a deterministic, reductionist approach, complexity and systems science focus on a non-reductionist, nondeterministic approach that includes emergent behavior. "Complex systems research addresses at a fundamental level, the behaviors of interdependent entities."[3] However, culturally, this research is not yet well accepted in engineering.

Complexity and systems science approach interdependencies in a manner that connects well with other genres of literature, such as theories on interdisciplinarity.[4, 6, 8-12, 16, 17, 46-51] In these literatures, interdependencies are assumed to be fundamental to understanding a system. In traditional engineering methodologies, a reductionist understanding of the parts of a system is favored over a complex understanding of the interrelations of the parts. A complex view of engineered systems was critical to this study as many of the respondents who were a part of this study held this perspective on systems and much of the social science literature connects well with it.

Literature on concurrent and collaborative design was also considered in this study. This literature addressed more of the social aspects of design that were inherently part of the current work. Olsen and Heaton "view design as a product of human activity" where the "field of constraints" that defines designing are "both social and technical" and the "social nature of the process is vital."[52] This article also draws on the literature and language of organizational sensemaking, describing "mindfulness" and "enactment" as inherent to designing. Creativity in the design process is described

in another, similar article as moving away from the notions of "unfettered freedom" but towards creative practices that included "improvisation, experimentation, and networking to bring about change."[52] The tenets of sensemaking that are referenced in these articles were also seen in the current study. Further discussion on sensemaking occurs later.

In another article, Cummings notes: "Increased complexity in design has both social and technical aspects. Not only are the technical problems becoming more difficult, such as learning to work with new materials, or learning to cope with changing regulatory environments, but the social demands that they bring is also changing. People from different cultures, who may have never worked together before, are brought together and expected to quickly bridge striking cultural differences and become productive with one another."[3] This article also highlighted an observation that emerged from this study, where traditional views of practices in engineering system design that focus on software and hardware integration do not account for "a process that is necessarily social, interactive, and iterative. Here the formulation of suitable process representations is more difficult, due to the dynamic and complex nature of social interactions."[3]

In Klein, et al, a complex systems view is adopted to analyze collaborative design.[36] In this article, the authors report that non-linear networks are a more accurate method of representing innovative design than the typically assumed top-down view adopted for routine design. In the current study, the respondents frequently operated in a much more networked manner than the hierarchical manner assumed by current organizational structure and engineering methods.

Given the networked manner of much of the interactions between engineers, literature on social networks was also reviewed for this study.[53] For example, Baker's work on social networks in organizations describes the impacts of positive or negative networks in organizations.[54, 55]

In the area of knowledge management in dispersed organizations, this study draws on literature on knowledge transfer across boundaries, distributed and collective cognition, and collaborative work environments.[12, 46, 49, 56-60] This diverse body of

literature highlights different aspects of knowledge in organizations that are pertinent to the current study.

In examining knowledge management across boundaries, Carlile integrates three different perspectives on boundaries and knowledge management: knowledge as "a thing to store and retrieve," "the importance of a common meaning to share knowledge between actors," and "how different interests impede knowledge sharing." Carlile further explores the "negative consequences of the path-dependent nature of knowledge" in settings where innovation is desired. [58],[56] The path-dependency of knowledge encouraged examination in the current study on the origins and path of the interactions between disciplines. In many cases this path inherently crosses many boundaries, including culture. While the literature on knowledge management across boundaries consistently describes significant challenges such as language, working across boundaries also has important positive artifacts that many respondents in this study described. "Boundary crossing stimulates the formation of trading zones of interaction, structures, and new categories of knowledge."[46] As existing knowledge is questioned, it is also transformed and advanced by the interactions.

This enacted and emergent characteristic of knowledge is further highlighted in the literature on distributed and collective cognition where the focus is less on knowledge transfer, but rather on knowing in practice where "knowing is not a static embedded capability or stable position of actors, but rather an ongoing social accomplishment."[49] While distributed cognition research includes research on the interaction of the mind with specific artifacts such as databases, this study focuses on distributed cognition research as it relates to groups of minds in interaction with each other. In the latter, the literature emphasizes the deeply social, interactive, and reflexive nature of knowing in practice.[49]

Madhavan, et al note: "The individual brings to the situation his or her repertoire of skills, knowledge, and strategies, which affect and are affected by the situation."[57] In affecting a team and being affected by a team, individuals are engaged in a "co-constructive relationship between human cognition and work" where competence is increased through interactions with others with different backgrounds.[49, 57, 61] Hence, knowing is enacted as the team interacts. Glynn describes organizational

intelligence as "a social outcome."[62] Hence, collective, enacted knowledge is inherently somewhat tacit and virtual as there is "no place for the information about this distribution of knowledge to be available to all members implicitly."[49, 63]

The co-constructive nature of knowledge transformation in a diverse team scenario is also noted in literature on complex design problems. Arias et al provide a summary of the complementary connection between research on knowing in practice and designing complex artifacts:

> "The predominant activity in designing complex systems is that participants teach and instruct each other [Greenbaum and Kyng 1991]. … Complexity in design arises from the need to synthesize different perspectives of a problem, manage large amounts of information relevant to a design task, and understand the design decisions that have determined the long–term evolution of the design artifact. … Relevant knowledge, which needs to be drawn out of and synthesized from the perspectives and expertise of the contributors, does not already exist and cannot simply be passed on by those who have it to those who need it. Therefore, approaches are required that view learning as collaborative knowledge construction [Scardamalia and Bereiter 1994] and expertise as a relative concept [Fischer 1993]."[63]

The emphasis on the social nature of the co-construction of knowledge in organizations and in large design teams also suggests that sociologically-oriented literature was also important to the current study, since "cognitive frameworks such as distributed cognition do not explicitly account for cultural issues."[61] Further, the R&D and early design activities studied in this research effort take place in time scales of years and even decades, making social and organizational topics critical to understanding relevant aspects of the research domain.

As such, literature in the broad field of Positive Organizational Scholarship (POS) was also reviewed for this study. This diverse body of literature includes numerous theories that focus on positive deviance in organizations, where enabling or creating capability building in organizations is a guiding principle.[64-66] In particular, the research on High Quality Connections (HQC) and building positive social capital helped frame much of the analysis of the social aspects of the data. HQCs are interpersonal connections that can be momentary and short term (not necessarily a deep relationship between the individuals) but "can have a profound impact on both individuals and entire organizations."[67, 68]

Essential ingredients of HQCs are "mutual positive regard, trust, and active engagement on both sides."[68] Several respondents in this study described these essential ingredients when discussing what was important in working across disciplines. For many respondents, these social ingredients were more essential than engineering aspects. HQCs are an important enabler to positive social capital in organizations, where social capital refers to the many resources that flow through and are an integral part of networks of relationships.[67] As noted earlier, the networks of work relationships are an underlying theme in the current study. In particular, the work by Cross, Baker, and Parker identified people considered as "energizers" in their organizations. The energizer is defined as "someone who can spark progress on projects or within groups." In doing so the energizer in social network attracts "commitment from other high performers" and greater attention from colleagues, such that others are "*much* more likely to seek information and learn from energizers."[69] In the current study, every respondent described people that excelled at enabling connections across disciplines in their organizations, using descriptors that map to the research on energizers.

Another genre of organizational theory that was used heavily in this research is sensemaking theory which delves into the "micro group levels of analysis" that helps to identify some of the intricate cognitive and social processes required for high organizational performance.[70] As noted by Weick, Sutcliffe, and Obstfeld, "To examine sensemaking is to take a closer look at the context within which decision-making occurs."[71] Whereas decision making is about strategic rationality (to determine what to do next), sensemaking is about contextual rationality (to make sense of what is happening).[72] In addition, sensemaking includes and extends beyond organizational leadership analyses. For example, Pye suggests that an analysis of sensemaking may be "more important than that of leadership because it is more inclusive and draws in other crucial elements of everyday life in organizations which are overlooked by much of the leadership literature."[73]

Sensemaking highlights the influence of identity, social context, enactment, retrospection, cues, plausibility, and the on-going nature of work in organizations.[74] Here, I will apply a few of these tenets to the research topic. In engineering

organizations that are organized by specialties, identity may become less clear during interdisciplinary interactions, for a researcher may ask: Who am I in this "between departments" world? Social context may also be ambiguous and perhaps intimidating during interdisciplinary R&D, where employees are not certain how to be credible with, or even respected by, unfamiliar departments. In early design, each researcher has innumerable cues and insufficient social relationships with or technical expertise in another department to facilitate selecting the salient cues or making better sense of the ones chosen. Hence, researchers must enact their next steps relying upon only plausible assessments rather than accurate assessments.

The theory of sensemaking also distinguishes two information-processing scenarios in organizations: uncertainty and ambiguity. Just as uncertainty has been a common focus in MDO research in engineering for several decades, psychologists and organization theorists have studied uncertainty in the social sciences since the mid-20th century.[75] The two perspectives on uncertainty resonate. In organization theory, the definition of uncertainty is the absence of information, where one seeks answers to explicit questions.[75] In engineering, uncertainty similarly deals with lack of knowledge and the often unpredictable difference between what data is available and what is needed to confirm predictions. In engineering, statistics and probability may be used to help reduce uncertainty.

Ambiguity (or equivocality), on the other hand, is primarily discussed in organizational theory research and deals with a lack of understanding or confusion that is common in organizations where "participants are not certain about what questions to ask, and if questions are posed, the situation is ill-defined to the point where a clear answer will not be forthcoming (March and Olson 1976)."[75]

High levels of both uncertainty and ambiguity exist in conducting research, development and early design of LaCES, and the inherent interdependence (and hence interdisciplinarity) between disciplines places further challenges on information processing needs. Though many respondents described their principal informational needs as having challenges related to uncertainty, many of their descriptions more aptly apply to challenges related to ambiguity. For example, during interdisciplinary interactions, the amount and variety of information one receives greatly increases;

however, there are both "multiple and conflicting interpretations"[75] of this information that create confusion and a lack of clarity.

Whereas additional, specific data helps to address uncertainty, problems and priorities need to be defined to help address ambiguity. Figure 3 shows the different communication styles and organization practices for addressing uncertainty and ambiguity.[75] Sensemaking theory suggests that a balanced approach to information processing is needed to foster interdisciplinary interactions such that both high amounts of numeric data via less personal media is received as well as high amounts of face-to-face time via more personal media. Respondents consistently confirmed this aspect of sensemaking theory, while noting that the tendency in their organization is to provide additional numeric data.
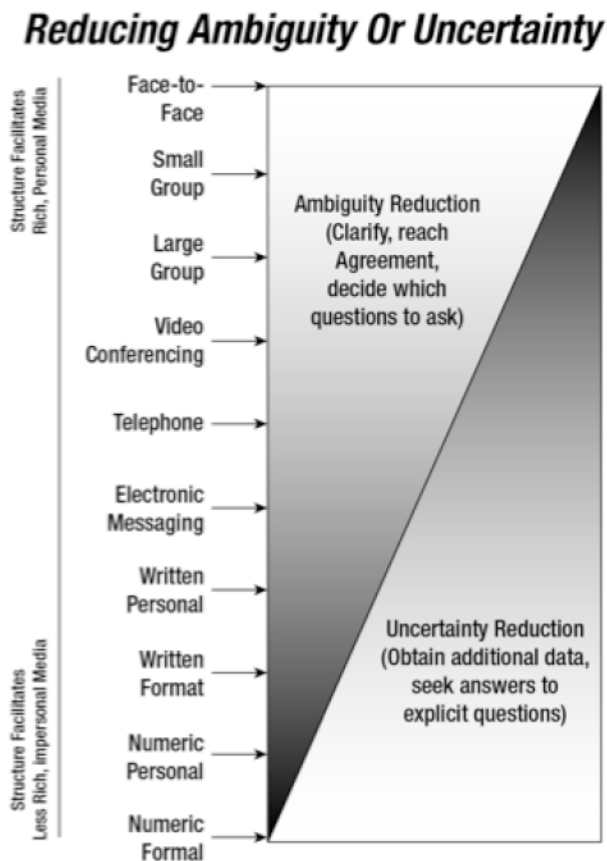
Figure 3 Communication Styles for Ambiguity or Uncertainty from Daft, 1993

The importance of several active and adaptive organizational concepts is also woven through much of the literature on sensemaking. Concepts such as improvisation, flexibility, updating, and continual input to keep what you have obtained within the organization are repeated in several papers (Blatt, et al.,[70] Maitlis, et al.,[76] Weick and Roberts[4], Schulman,[77] Pye[73] and others). The disintegrative nature of other key organizational properties, such as attention, close coordination, and mutual trust, is often noted.[78] Starbuck and Nystrom, summarize by stating: "A well-designed organization is not a stable solution to achieve, but a developmental process to keep active."[79] The insights on the need for continual organizational attention and improvisation guided data analysis to be cognizant of both established practices and ongoing efforts toward updating practices.

Concepts of improvisation and flexibility are also central to research on high reliability organizations (HROs) – a genre of research with foundations in sensemaking theory. Work by Sutcliffe and Weick on HROs suggests that adaptively organizing for increasingly complex environments is necessary, as opposed to using static organizational structures.[80] Their work focuses on organizations that operate in high-risk scenarios such as aircraft carrier operations, air traffic control, and fire fighting. While the current study is focused on R&D and early design work not the high-risk operations used for HRO research, considerable commonalities exist between HRO research and LaCES R&D and early design.

For example, Roberts notes that another key characteristic of HROs is "extreme interdependence," and that "HROs are characterized by both advanced technology (requiring specialist understanding) and high degrees of interdependence (requiring generalist understanding).[81] Schulman, 2004, points out "these systems due to their complexity are formally underdetermined; that is, they are capable of assuming more conditions or system states than can be planned for or anticipated in formal designs *[and R&D]*. This means they have the capacity to confront managers *[and researchers]* with problems of high variety and significant novelty" (emphasis added).[77] Another example where R&D of LaCES mirrors HROs is in the area of large-scale testing and evaluation, where "the consequences and costs associated with major failures in some technical operations are greater than the value of the lessons learned from them."[82]

This results in "an organizational process colored by efforts to engage in trials without errors, lest the next error be the last trial."[82]   The literature on HRO addressed the highly undetermined and financially risky nature of LaCES R&D work where standard operating procedures are necessary but insufficient in practice, given the unpredictability of many R&D efforts.

An organizational sensemaking framework called the Cynefin framework also draws on sensemaking theories and describes the enacted nature of interdisciplinarity as one of a "complex" mode of organizational operation.[83] This framework also draws from the theories of complexity similar to several previously noted articles.   This framework and numerous other articles cite the growing "complex nature" or "complexity" of problems as a principal reason for interdisciplinary efforts.[6-9, 11-13, 16, 17, 46, 48, 84] Klein writes: "The complexity of problems that professionals face in practice creates a sense of interdisciplinary necessity. Complex problems pull research away from classically framed disciplinary problems. By their very nature they are open ended, multidimensional, ambiguous, and unstable. Considered "wicked" and "messy," the problems at the heart of many professional fields cannot be bounded and managed by classical approaches to the underlying phenomena (Mason and Mitroff 1981; Rittle and Webber 1973)."[46]

In a similar vein, Repko notes: "Today, interdisciplinary learning at all levels is far more common as there is growing recognition that it is needed to answer complex questions, solve complex problems, and gain coherent understanding of complex issues that are increasingly beyond the ability of any single discipline to address comprehensively or resolve adequately."[6] The literature on interdisciplinarity provided a rich source for better understanding the nature of the interactions between the respondents studied.

Beginning with a disciplinary view that many respondents originated from, Repko notes the complementary nature of single-disciplinary research with interdisciplinary research, stating: "the disciplines are foundational to interdisciplinary work because they provide the perspectives, epistemologies, assumptions, theories, concepts, and methods that inform our ability as humans to understand our world."[6] At the same time, the disciplinary differences are the source of the productive argument that

underscores interdisciplinary work. "Difference, tension, and conflict emerge as important parts of integrative process. They are not barriers that must be eliminated; they are part of the character of interdisciplinary knowledge."[46]

Many respondents articulated the inherent tensions and a sense of messiness in their interactions. Klein describes that interdisciplinarity "requires accepting, from the outset, the unforeseeable and the productive role of misunderstanding. A sense of the new and surprising is decisive in mutual exchange and dialogue. The result is not necessarily consensus or unity; dissent will remain a thorny issue."[46] Accordingly, research on interdisciplinarity repeatedly emphasizes challenges of communications where "all interdisciplinary activities require translation and negotiation."[46]

One particular area of convergence of different genres of literature that was most beneficial in this study was the area of knowledge transformation though interpersonal interactions. The literature on distributed and collective cognition, sensemaking, knowing in practice, social capital, creativity, interdisciplinarity, and design all identify the beneficial role that human-to-human interaction has on knowledge, where knowledge is not simply transferred but knowledge is transformed. All of these genres of literature describe knowledge as enacted and co-constructed through on-going interaction where argument and ignorance are inherent and useful. Thus, a more comprehensive understanding of the problem being addressed (in this case a future system design) is enabled by interdisciplinary interactions between disciplines. Interdisciplinarity is described as knowledge integration where "the goal, purpose, or result of the research process is to construct a more comprehensive understanding."[6]

In studying the challenges for distributed, interdisciplinary teams, Haythornthwaite et al, note that while much literature and organizational effort is focused on making "tacit knowledge explicit for transfer to others" their research suggests that "contemporary teams face a more complex set of issues as they engage in joint knowledge construction. Contemporary team members find that cannot simply transfer their previous collaborative skills to a widely distributed, interdisciplinary arena, but must continually renegotiate a wide range of research and work practices thought to be already established." Their research also distinguishes novices and experts suggesting that while novices may focus on "transfer," experts on distributed,

interdisciplinary teams focus on "joint problem-solving, shared cognition and co-construction of meaning."[12]

As previously noted, the fusion of the diverse genres of literature that informed this study was perhaps the most enlightening source of research. While some of the literature provided contrasting views, the areas of commonality focused on knowledge transformation, interpersonal relations, and collective action, all viewing engineered systems from a complex perspective. These dominant themes form the basis for the current study.

Chapter 2: Research Methodology

Summary

In this chapter I provide a theoretical justification for the methods used in this study and the strategy for the research design linking research methods with the desired research outcomes. This chapter begins with an overview of the research questions that drove the study design then presents the motivation for using a qualitative approach. The overall research design strategy is then discussed including the integrative data analysis method. Next, each research method is described separately including data collection and first order data analysis. The comprehensive survey and interview protocols appear in the appendix along with documentation of the approvals for research using human subjects.

Introduction

The goals of this study focused on understanding existing practice. The research questions guiding this work included:

1) *What are current perspectives on and practices in interdisciplinary interactions during research and development and early design of LaCES?*
2) *Why might these perspectives and practices prevail and persist?*

These research questions were well suited to a qualitative approach that works well for answering "how" questions as opposed to "how many" questions.[85] The research design consisted of a three-fold, integrative approach that combined survey, interview, and ethnographic research. In this chapter I present the motivation for using a qualitative approach and the overarching research design and data analysis strategies before detailing the components of each of the three research methods used.

This approach did not focus on using traditional domain decompositions provided by existing theories. Rather I focused on inductively finding descriptions based on empirical data from the surveys, interviews, and ethnography. This is a descriptive analysis approach that "attempts to understand cognitive work practices from the

perspective of the subject, in the contexts where the subjects find meeting" rather than in a simulated research laboratory environment.[61]

As a qualitative research approach is less common in the field of engineering, I describe its foundations and methods herein beginning with a rationale for using qualitative methods in this study. Several references provide considerable information on conducting qualitative research and were used to inform this study.[85-99] Subsequently I will describe the three methods used along with the strategy for data collection and data analysis.

Motivation for Using a Qualitative Approach

Though commonplace in the social sciences, qualitative methods are less frequently used in the field of engineering. Qualitative analysis often further defines the many facets of a problem before attempting to investigate it quantitatively. Qualitative analysis can also provide depth following quantitative work. "The broad purpose of qualitative research is to understand more about the human perspectives and provide a detailed description of a given event or phenomenon"[93] and "for understanding the world from the perspective of those studied (i.e., the informants); and for examining and articulating processes."[85] As such, qualitative research is sensitive to context and takes a holistic perspective that includes the social, historical, and temporal contexts.[93]

Qualitative methods serve the current study well, particularly an ethnographic study, because the goal is to describe and conceptualize a wide variety of perspectives.[98-100]. Additionally, qualitative methods also facilitate the goal for a formative study "intended to help improve existing practice rather than simply to determine the outcomes of the program or practice being studied" (Scriven, 1967, 1991 as referenced in [88]).

In this research, there were many open questions and little previous work on which to build a hypothesis about the barriers and enablers of interdisciplinary interactions in LaCES. Additionally, I could not influence the environment in such a way as to run a controlled experiment and attempts to do so would exclude some of the

data that were important to collect in the study. For example, I sought to understand the totality of the organizational context including culture, norms, hidden agendas, etc. Thus, in an effort to transcend the constraints of a laboratory environment and evaluate actual work settings, I encouraged respondents to expand upon their experiences to the fullest and observed practice in its natural environment.

One option to study the research and development practices of LaCES could have been to use a quantitative approach, recruiting a large random sample of those whose work is related to LaCES and collecting data through a self-report survey with quantifiable multiple choice questions where respondents could be asked to rate a number of items as having an influence on their interdisciplinary interactions. However, the limitation of this approach is that I would need to develop a survey instrument that listed the important factors that play a role in interdisciplinary interactions in the available multiple-choice answers. Due to the limited research in the area, this list of factors would be anecdotal and biased by my own experiences. The list provided to respondents might not have captured the real barriers or enablers of interdisciplinary work.

Additionally, interdisciplinary interactions are complex phenomena and respondents are likely to interpret what they are in different ways. A multiple choice survey format may not have provided sufficient detail to understand the important distinctions across participants or to discern intricacies in how one person's definition compared to another's. Such a survey would result in a limited analysis of the complex phenomena under study, greatly limiting the ability to explain why or how these interactions occurred or compare the ways in which a factor had an impact across multiple participants.

Using qualitative methods for this study allowed the respondents to freely describe the real barriers or enablers of interdisciplinary interactions by giving in-depth examples they have experienced in practice. Their answers were not confined by multiple-choice options that would be limited by the available research findings. Variations in experience among the participants were also captured via the open-ended nature of the qualitative approach.

In general, the research questions should determine the research method, not

the contrary.[101] For this study I sought to investigate why and how interdisciplinary interactions occurred, the importance various players placed on these interactions, how these interactions were defined by people in different organizational roles, and what factors supported and impeded the occurrence of these interactions. To answer these questions, the collection of in-depth data to understand the context and experiences of practicing engineers and scientists was necessary. A qualitative approach allowed a naturalistic environment, investigating the real-world setting of LaCES without manipulating it, and facilitating the study goal of understanding in a specific context.[89, 102] While quantitative methods would also add different insights to this study, the primary research goals were best suited by qualitative methods.

Integrative Strategy to Obtain Synthesized Findings

In this section, the integrative research methodology used for this study is described. Three different research methods were used to help examine different facets of the problem domain. However, the ultimate goal of this study was synthesis of the different data to enable an integrated, rigorous, and comprehensive analysis. Hence, I begin this discussion with a description of the integrative research design that included a strategy for synthesizing the data from the three different methods employed. Details of each individual research method are provided in the next section.

Research Design Strategy

The overall structure of the research design included a triangulation approach where data collected from open-ended surveys, semi-structured interviews, and ethnographic interactions and observations were synthesized. Each research method provided insight into distinct facets of interdisciplinary interactions during engineering systems R&D and early design. The multi-method approach chosen used:

1) Open-ended surveys to identify current perspectives;
2) Semi-structured interviews to provide detailed, concrete examples of practices; and,
3) Insider ethnography to provide a rich, descriptive account of cultural and organizational work life.[94, 97, 99, 100, 103-105]

The research design of this study was guided by principles of rigor in qualitative studies. Data were collected using three different methods to allow for synthesis and to strengthen findings during analysis. This approach aided in reducing researcher bias and improving the trustworthiness of the findings. Each data collection method unearthed different aspects of interdisciplinary interactions thereby significantly improving the "confirmability" of the findings. Additionally, each of the three data collection methods enabled the opportunity for "negative cases" that challenged preliminary themes. Peer examination from researchers in engineering, organization science, engineering education, and psychology further aided in cross checking interpretations.

Employing insider ethnography also allowed for considerable feedback in the form of sustained member checking from a wide variety of peers within LaCES R&D. Further discussion on insider ethnography is provided subsequently. Emerson, et al, note that "the task of the ethnographer is not to determine 'the truth' but to reveal the multiple truths apparent in others' lives,"[104] for "[any phenomenon] contains multiple truths, each of which will be revealed by a shift in perspective, method, or purpose... The task is not to exhaust the singular meaning of an event but to reveal the multiplicity of meanings, and... it is through the observer's encounter with the event that these meanings emerge." Mishler, 1970:10, as referenced in [104] Taking advantage of the ethnographic field setting, as preliminary findings emerged, they were presented to members of the organization who were blind to the research questions. Feedback was integrated and the findings were further refined and the process was repeated as necessary.

These three methods were integrated into an analytical approach that included: first-order analysis of data from each method by itself; followed by second-order analysis that integrates data and provisional findings from multiple methods to create updated findings; and concludes with a comprehensive synthesis that incorporates relevant theories and creates theoretical conceptualizations grounded in the empirical data and backed with theory. Ultimately, this analytical approach seeks to:

1) Present empirical data;

2) Explain the data through detailed descriptions;

3) Interpret the descriptions through conceptualizations;

4) Connect the descriptive and conceptualized findings to the research questions;

5) Support the findings with theory; and

6) Avoiding quantitative framing that can be misleading.

Integrative Data Analysis Approach: From Codes to Synthesized Analysis

The over-arching analysis approach was interpretive involving qualitative content analysis using theoretical sampling and methods of constant comparison (in keeping with the grounded theory methodology developed by Glaser and Straus).[98] Data analysis was inductive, guided by constant comparison methods, in which themes were identified, continuously compared to newly emergent themes, and revised based on the comparison.[98] As is common in a qualitative study, data from all research methods (ethnographic and survey data) were integrated and re-coded as new findings emerged and the research design was adjusted accordingly.[86] While a highly inductive data analysis approach guided the findings, to prevent assiduous theory avoidance, this work has theoretical underpinnings in several genres of literature as presented in the previous chapter.[85, 106, 107] Data were coded and re-coded via an iterative first-order and second-order analysis approach.

First-order analysis involved primarily focusing on data from an individual method. Here patterns in the data were examined to identify empirical groupings and descriptions. First-order analysis provided an organized, descriptive account of codes and preliminary themes. After first-order analysis, deeper (second-order) analysis was conducted by integrating the data and preliminary themes from all three methods to provide more dense descriptions of emergent concepts and where possible, also provide explanatory frameworks or conceptualizations to further clarify some phenomena.[103] For a few major themes, potential explanatory perspectives from existing social science theories were also considered.

In sum, this second-order analysis focused toward providing theoretical perspectives that seek to interpret and explain the first-order analysis.[103] This "theoretical perspective is grounded in, and emerges from the first-hand data (cf. Glaser and Strauss, 1967)."[108] Second-order analysis entailed discovering meta-themes that

encompassed multiple codes from open-ended survey questions and interview responses and ethnographic observations to derive explanatory conceptualizations to provide a more theoretical perspective on the findings.

While the goal of the explanatory conceptualizations created in this study is not focused toward building theory, a theory-building lens was used in creating them. "Two foci in developing theory are discovering patterns and identifying processes."[109] Theory may be viewed as "plausible relationships proposed among concepts and sets of concepts." (Strauss and Corbin, '94 as quoted by [109]) Thus, my goal in the conceptualizations derived was to understand the "orderly relationships among disparate phenomena." (Goodenough, 1964 as quoted by [103])

The synthesized analysis of all of the data of this study was driven by exploring patterns, processes, and relationships to conceive of an overall story that illuminated the heart of engineering practices and perspectives on interdisciplinary interactions. Except where noted, the findings herein are a second-order synthesis of all of the codes, themes, and meta-themes from all of the data. Triangulation was an essential aspect of the research design.

To echo what is well documented in qualitative research theory literature, I note that a quantitative frame for analysis of the data is an inappropriate frame given the sample size and research methodology used. Accordingly, statistical generalizability is not the aim for this study but rather generalizability in the context of R&D in LaCES is the appropriate frame for considering potential transferability of these findings to other contexts.[109]

Individual Data Collection and First-Order Analysis Methods Employed

Survey Research

Qualitative survey research with open-ended questions was implemented to reach a more diverse sample of respondents and focused on identifying current perspectives on interdisciplinary interactions. To enable respondents to expand upon

their experiences without constraining them to specific answers, an open-ended survey instrument was used. The written survey was conducted at the NSF/NASA Workshop that included multiple organizations and was entitled "Large-Scale Complex Engineered Systems, From Research to Product Realization."[21] The senior leaders and researchers invited to participate in the workshop provided a convenience and purposeful sample of a rare participant pool.[85, 98, 109]

The 62 survey respondents represented a wide variety of backgrounds and extensive experience in engineering, including practicing researchers, project leaders, systems engineers, and executives in industry and government, as well as leading academic researchers in engineering design, organization science, optimization, and economics. The respondents (most of whom did not know each other) also represented a wide variety of organizations from different government agencies, corporations, and universities. The sample size is significant considering the difficulty of garnering responses from a multidisciplinary group of LaCES experts from different organizations. While these participants were selected based on their prior experience with R&D for LaCES, there was no intent to collect a representative sample for this study. Rather, this group was selected because they are in the position, based on their extensive experience, to provide their perceptions of R&D within LaCES.[89]

The survey design was guided by the research questions and preliminary data from ethnographic observations. It included simple instructions for obtaining short, written answers to seven open-ended questions. The written instructions printed on each survey were: *"Please consider your first-hand experiences with research in large-scale, complex engineering systems."* These instructions were followed by:

1) *How important do you think interdisciplinary interactions are for complex systems?*;

2) *Please describe the potential benefits to interdisciplinary interactions;*

3) *Please describe the potential negatives to interdisciplinary interactions;*

4) *Please describe things that encourage interdisciplinary interactions;*

5) *Please describe the obstacles to interdisciplinary interactions;*

6) *Please provide some background context for your experience:*

   Where do you work?

   What do you do for your occupation?

How many years of work experience do you have?; and,

7) *Please add any other comments you wish below.*

An example of the survey instrument is provided in the Appendix. The participants completed the survey on site within 30 minutes. The survey provided a unique assessment of current thinking on interdisciplinary interactions and took place prior to the interviews, which also guided the interview design and analysis. The survey responses were integrated with ethnography to discern possible underlying dimensions or patterns in the data to create the first-order analysis provided in the next chapter.[108]

The survey data were analyzed by hand and comprehensively examined twice with some portions of the data reviewed multiple times. First-order analysis of the survey data entailed considering repetitions, similarities, and differences of concepts, being mindful of each individual respondent's answers as a whole and grouping the responses question by question.[90, 98, 106] Ethnography was critical for understanding several nuances, metaphors, and analogies in the survey data such as "stove-pipe" for line organizations and "NIH" for "not invented here" which refers to a long-standing term to describe internal groups who are not very open to outside ideas or methods. First-order survey analysis appears in the next chapter.

Research Setting for Interviews and Ethnography

The interview and ethnographic data were taken from within a LaCES organization given the pseudonym Kappa. Kappa is a large science and engineering organization that spans the full spectrum of the engineering process, from basic, fundamental research to the operation of large, extremely complex engineered systems. The interview portion of this study focused on the basic research through early conceptual design efforts within the organization. Kappa has approximately 20,000 employees distributed at several sites across North America with various, much smaller operations and partnerships around the globe. Kappa continues to enjoy a positive reputation for hiring engineers and scientists of high competence and for solving innumerable technological feats since it first opened its doors several decades ago. Kappa continues to boast hundreds of patents a year. Despite its well-earned

reputation and unarguable successes, Kappa faces the challenges of many large, geographically-distributed technology organizations with a long history: change can be slow, processes and paperwork can be dense, communication can be unwieldy, organizational consistency is challenging, and innovation can be both stellar and stale. Long-term employees, who often remain with Kappa for most or all of their careers, form the bulk of Kappa's workforce.

Interviews

The semi-structured interviews focused on obtaining detailed, concrete examples of cross-disciplinary practices and rich descriptions. Twenty respondents were carefully chosen with the help of ethnography to provide a balanced sample considering years of experience, job site locations, leadership and staff positions, and diversity of engineering tasks. The interviews offered comparative data "for understanding the world from the view of those studied" and helped to unfold the meaning of the respondents' experiences.[85, 92] The interview was designed after taking into account preliminary analysis of survey and ethnographic data.

Purposeful sampling was used to gather data from the following groups:
- Age: Younger and older (a few junior level but mostly senior level engineers with 20 or more years of experience represented)
- Gender: Male and female
- Job site: Two different geographic sites, separate by several states (equally represented in the sample)
- Official Role: Supervisory line managers, team leads, and staff engineers
- Cross-disciplinarity: single and multi-discipline researchers including those who work in MDO and systems analysis
- Unofficial role as natural integrators: those viewed as excellent integrators and those viewed as less than stellar integrators (based upon ethnographic data such as getting consensus from talking to many people in the organization)
- All worked in different projects of the same large R&D program

An example of the entire interview protocol appears in the appendix. Example questions asked during these interviews included: *"I'm interested in hearing about an*

experience you had in working with someone outside of (their home area of work). Tell me about it." "Can you describe what challenges you faced?" "I'd like to hear about what you gained from the experience?"

All interviews lasted between 1 to 3 hours long. All were taped, transcribed verbatim, and cleaned of all identifying material. Coding was initially conducted while re-listening to each interview recording to ascertain tone and address any errors in transcription. The software NVivo was used to analyze all of the interview data and organize some of the ethnographic data. NVivo provides an analytical workspace to organize and analyze unstructured information such as transcripts from semi-structured interviews and observations from ethnography.[110]

First-order analysis of the interview data focused on two steps of "open coding" then "axial coding."[92, 94, 98, 106] During "open coding" each interview was treated as a separate case to understand the central message of that respondent. During "axial coding," I compared fragments across interviews to obtain an inventory of characteristics of meta-codes and preliminary themes. The goal of this step was to seek patterns to validate, confirm, or cast doubt on the developing meta-themes. As with the survey data, ethnographic insight was absolutely crucial to understanding and interpreting innumerable comments from the respondents.

Ethnography

Ethnography involves "immersion in the social context being studied."[94] Insider ethnography goes further by undertaking research in and on an organization while being a complete member of the organization.[99] Ethnographic research for this study was primarily conducted in aerospace R&D settings via 20 years of insider involvement and extensive interaction with a wide variety of aerospace R&D entities including government, industrial, and university laboratories. The long duration of the insider ethnography provided critical insight to discern "the more subtle, implicit underlying assumptions that are not often readily accessible through observation or interview methods alone."[104] Ethnography included participant observation with informal, unstructured interviews. Ethnography was particularly important to this study since many processes in R&D of large engineered systems take years or even decades to

complete and this research sought to account for the rich contexts that unfold over time lengths that were significant to the study data.

While insider ethnography creates some methodological challenges such as potentially increased researcher bias, for this study, it was critical for obtaining the access necessary for understanding innumerable organizational aspects such as silent organizational divisions, charades or cover stories, unspoken rules, and organization culture, which "always runs much deeper than its published claims and its members behavior."[97] Brannick and Coglan write that for insider ethnography, "the researcher is an engaged participant whose critical and analytical observation of the culture is integral to the research activity. Successful practice is the result of personal knowledge, judgment, and experimental action."[99] As noted, several steps were taken in the research design to improve validity of the findings including triangulation, peer review, member checking, and seeking potentially "negative cases." In analyzing the ethnographic observations, I reflexively questioned the observations by considering questions such as: Under what conditions are certain practices likely to occur? And, upon what factors does variation depend? In all cases, member checking was extensively used during ethnographic analysis by talking with respondents that were blind to the research questions.

First-order analysis of ethnographic data was documented using thematic narratives that were derived from themes that emerged from patterns in events and informant accounts.[104, 108] However, maintaining anonymity was imperative in documenting the ethnographic observations. To address this, I used several analytical techniques including empirical and theoretical generalizations[103] and semi-fictionalized ethnography.[100] An empirical or inductive generalization moves beyond a descriptive summary (such as 'the researcher conducted an x-type test by using a y instrument') by creating an accurate generalization that captures principal characteristics of the finding (such as 'all researchers carefully selected instrumentation specific to their testing needs'). A theoretical generalization seeks to explain the empirical generalization and provides the basis for building or confirming theory (such as 'specialized instrumentation is needed for the different types of tests conducted to accurately capture detailed data in a format that is useful for further study'). In semi-

fictionalized ethnography[100] events from one or more observations are combined to create a unified story or depiction that cannot be traced to a specific individual or occurrence. Allegories and analogies are used in this report to convey ethnographic observations in an accurate yet anonymous manner. This approach enables a thorough discussion of the findings while wholly protecting the anonymity of the respondents and avoiding inherent sensitivities related to any one real example.

Synthesized Findings from all Three Methods

As noted earlier, data from all three research methods were integrated to create the synthesized findings presented subsequently. Though specific individuals served as respondents for the survey and interview portion of this research (62 from the open-ended surveys and 20 for the semi-structured interviews), their data were integrated with scores of respondents who provided input for the ethnographic portion of this research. The unit of analysis of this study is a group level of analysis. The synthesized findings represent a triangulated analysis based on input from all sources of data. In presenting the synthesized findings in this report, supporting data from a wide range of respondents are used with bulleted lists used to indicate answers from different respondents. Where possible, the examples of supporting data for each finding is selected from one or more respondents who articulated the finding the most succinctly. However, note that each finding is supported by considerable data from a wide variety of respondents from the different research methods.

Additionally, respondents used terms for working across disciplines inconsistently (cross-discipline, multidiscipline, interdiscipline, and transdiscipline). Where possible, the meaning of their words was determined by the context of their descriptions. While gathering empirical data for this study, the misunderstanding of these terms was common among respondents. For example, during the survey, which occurred before the interviews, participants were asked about their first-hand experiences regarding *interdisciplinary interactions* in research for large-scale complex engineered systems. In hindsight, it is clear that the respondents likely considered all types of cross-disciplinary interactions in their responses. Hence, in analyzing the survey data (as well as all subsequent data), I assumed respondents provided a broad perspective on cross-

disciplinary interactions. As a result of the misunderstanding of terms, I began each interview with a statement such as: *"I realize there are many terms used to describe working across technical disciplines. There's 'multidiscipline,' 'interdiscipline,' and even 'transdiscipline.' To keep things simple, I will sweep all of these terms into what I will call 'cross-discipline' during this interview. Do you have any questions regarding that?"*

In the next chapter a description of the first-order analysis of the survey data is presented as this data was obtained early in the research effort and it greatly shaped the subsequent data collection and integrated analysis. The remainder of this report focuses on the synthesized analysis based on all data obtained.

Chapter 3: First-Order Analysis with Provisional Findings from the Survey

Summary

The survey portion of this research effort provided significant insight that greatly shaped subsequent research design and analysis. This chapter presents the first-order analysis of the data from the survey, prior to the integration of data from the interviews. Inherently, all data includes perspectives gained from ethnography. From the survey, several strong consistencies emerged. Nearly all respondents consistently replied that interdisciplinary interactions were very important. Stated benefits are primarily related to engineered system improvements such as risk mitigation and cognitive improvements such as enhanced system understanding and innovation. The improvements derive from what respondents describe as an increased awareness and perception of system behavior. The noted benefits and related improvements are largely intangible, emergent, and realized in the long-term making quantitative evaluation of the efficacy of interdisciplinary interactions extremely difficult and impossible in some aspects.

Social and organizational topics consistently emerged as the primary encouragements and obstacles to interacting across disciplines with associated implementation challenges being noted as well. Confusion, coordination, communication, and organizational support, or lack thereof, were often noted. These provisional findings guided subsequent efforts toward clarifying system, cognitive, social, organizational, and implementation aspects of working across disciplines. The lack of mention of common integrator roles that are built-in to most organizations also fostered increased scrutiny in research efforts after the survey. In this chapter, a high-level summary of the first-order survey codes is presented first, followed by samples of raw data from each question. Meta-themes from the survey are then defined with provisional findings. These provisional findings are synthesized with data from the interviews and ethnography to establish the integrated study findings that are discussed in depth in the chapters that follow.

Summary of First-Order Codes from the Survey

Table 1 provides a summary of inductive codes that emerged from the "raw" survey responses for the first five questions. The codes are listed by question, organized with codes that emerged from the greatest number of responses at the top, to the least number of responses for that question at the bottom, with no effort to correlate responses among the questions. Recognizing that a quantitative frame for analyzing the survey data is methodologically inappropriate for this sample, this listing and approximate ordering of codes is provided to give a wide qualitative view of the data received.

Table 1 First Order Codes from Open-Ended Survey

Q1:Import-ance	Q2: Benefits	Q3: Negatives	Q4: What Encourages Interdisciplinarity	Q5: Obstacles
Very Important or Essential Potentially Very Important	Enhanced Knowledge: Increased Understanding & Knowledge/ Diversity of Thought Problem Mitigation and Understanding of Interfaces Innovation and Creativity Broader, Systems-Level Understanding and Broader Solution Space Improved System Design or Performance Increased Efficiencies in Sys Development & Org Practice/ Communication	Organizational Confusion, Coordination, & Conflicts Communication Difficulties/Lack of a Common Language Additional Time Req. Mitigating Single Discipline Biases & Impacts Org. Cultural Challenges Challenges in Learning and Understanding Potentially Wasted Resources Negative Emotional Response No Negatives	Multidiscipline Experiences & Individual Openness Relationship Building Incentives Org. Culture & Openness Proactive Teaming Mgt. Support/Leadership Technical Need Proximity to Colleagues Interactive Activities Org. Structure & Flexibility Increased Awareness Common Goal Specific Org. Roles/Functions Communication Resources/Means	Communication and Language Barriers Emotional Response Cost and Time Group Dynamics Culture Organizational Structure Career Concerns and Incentives Lack of Requisite Skills Org Processes Proximity to Colleagues Leadership

Meta-Themes and Samples of Raw Data

<u>Question 1: How important do you think interdisciplinary interactions are for complex systems?</u>

While most responses were multi-faceted, responses about the importance of interdisciplinary interactions were overwhelmingly consistent among nearly all respondents. Respondents noted the high importance of these interactions, with most respondents using strong descriptors, such as "essential," "critical," "very," "extremely," "crucial," "indispensable," and "paramount." The consistency of strong responses suggests that a very high value is placed on interdisciplinarity in the R&D of LaCES.

Yet this consistency of strong responses is quite surprising, as it appears to be in tension with the frequency of negative responses related to existing culture, poor emotional response, organizational structure, and perceived lack of incentives and leadership support. Since the survey was anonymous and the questions were open-ended, the consistency and vehemence of the responses were very likely not simply from respondents trying to "pay lip service" or endeavoring to appear politically correct in their responses.

<u>Question 2: Please describe the potential benefits to interdisciplinary interactions</u>

Most responses concerning benefits of interdisciplinary interactions in R&D can be grouped into two broad meta-themes: <u>system improvements</u> and <u>cognitive improvements</u>, the latter garnering more responses. These two meta-themes appear to be linked. For example, the cognitive benefits noted in some responses may offer additional awareness needed to enable the system improvements suggested:

- "Broader understanding,"
- "Shared knowledge,"
- "Emerging thoughts," and
- "Understanding of important trades,"

Respondents suggested these system benefits:

- "Risk recognition",
- "More elegant solutions",

- "Lower product costs due to re-engineering",
- "Better integration,"
- "Reducing 'downstream surprises' of 'emergent behaviors' from un-modeled interactions," and
- "Identifying second order effects that may be more significant than first order effects."

Many respondents cited opportunities for innovation and creativity as:

- "New technical solutions,"
- "Unforeseen capabilities,"
- "Diversity of thought," and
- "Innovative thinking."

Survey respondents articulated the benefits of learning and improved understanding as:

- "Knowledge transfer,"
- "Better view and perspective,"
- "Understanding the multiple domain problems,"
- "Understanding of the true interfaces," and,
- "Feedback mechanism: research to practice for validation, practice to research for understanding."

Salient aspects of the noted benefits are: 1) they are largely realized in the long term and 2) they relate to concepts somewhat intangible and emergent, and thus non-predictive in nature, making the perceived benefits very difficult or impossible to quantitatively measure or predict, particularly the cognitive benefits. An example is the highly emergent nature of learning. As new data (and hence, knowledge) is acquired during R&D, the system design that integrates the R&D results is updated in a manner not always predictable *a priori* and newly acquired understandings may provide greater benefit for future systems than for current systems. Another example is that it is very difficult to plan when, if, or to what degree the benefits of "risk recognition," "holistic systems thinking," and "richer idea generation" will manifest themselves as cost or time reducers or performance enhancers on the engineered system.

Question 3: Please describe the potential negatives to interdisciplinary interactions

The vast majority responses regarding the potential negatives associated with interdisciplinary interactions related to the meta-theme of <u>difficulties in implementation (the "how")</u>. The top four most referenced topics appear somewhat related, with common responses being:

- "Confusion,"
- "More coordination,"
- "Communication barriers," and
- "Time and effort."

Respondents noted repeated challenges related to language, terminology, and vocabulary when interacting across disciplines. Sample responses cited by several respondents included: "disparate levels of understanding of other disciplines;" "misunderstanding between people of different backgrounds with different terminology;" and a "breakdown in communication."

A sense of disorderliness and discomfort with interdisciplinary interactions appears throughout many responses. Examples of this include:

- "Makes people uncomfortable,"
- "Cultural rejection,"
- "Conflicting objectives and preferences,"
- "Less clear lines of responsibility," and
- "Challenge of different terminology, different practices, and processes."

This question also drew several responses regarding mitigating single-discipline bias such as, "experts in given fields may dominate over others for problems related to their field." And, potential negative impacts such as, reduced single-discipline focus and a "tendency to revert to stove pipe thinking." Another minor theme from the responses about the negatives of interdisciplinary interactions was a tension between the desire to avoid reducing the focus of single-discipline research and the desire to avoid the

dominance of any single discipline. Interestingly, many respondents who had very strong, positive responses for the importance and benefits of interdisciplinary interactions also noted a number of perceived organizational constraints toward implementing them.

<u>Question 4: Please describe things that encourage interdisciplinary interactions</u>

The predominance of responses related to what encourages interdisciplinary interaction may be grouped into two broad meta-themes of <u>social</u> and <u>organizational</u>, with minor themes related to <u>engineered systems</u> and <u>planning</u>. Numerous responses related to social concepts were articulated as:

- "Co-location,"
- "Trust,"
- "Tolerance,"
- "Openness," and
- "Working level relationships."

Organizational concepts were repeated by many and included:

- "Workshops,"
- "Organizational structure,"
- "Management support/patience," and
- "Incentives,"
- "Org culture," and
- "Integrative teams (IPT structure) and organic (vs. mechanistic) organizations."

The need for integrative activities was a common thread in the responses. Respondents noted that these activities were needed for social ("building respect"), geographic ("embedding"), organizational ("break functional management structures"), and increasing awareness ("seminars"). The need for improved incentive was noted by many as was a need for individual openness. Quite surprisingly, although there were many respondents who are MDO and systems engineering practitioners, and these roles exist in nearly all of the organizations represented, there were only three responses from all respondents to all questions that mentioned or referred to the

traditional roles of "MDO," "Systems Engineer," and "Chief Engineer." The absence of this expected response led to the development of a question during the interviews to further probe for more information.

<u>Question 5: Please describe the obstacles to interdisciplinary interactions</u>

The responses to Question 5 regarding the obstacles to interdisciplinary interactions may be grouped into the four meta-themes of <u>social</u>, <u>organizational</u>, <u>time/cost</u>, and <u>skills</u>. The social meta-theme encapsulates the majority of the responses to this question, examples being:

- "Language barriers,"
- "Terminology,"
- "Distributed location,"
- "Culture,"
- "Possible misaligned objectives," and
- "Disinterested teammates."

The social meta-theme also emerged from several, very descriptive single-word responses such as: "fear," "ignorance," "tribalism," "arrogance," "elitism," and "pride." Some of these latter responses suggest a defensive reaction in interdisciplinary interactions. The organizational concepts were noted as:

- "Rigid standards,"
- "Stove piped organizations," and
- "Poorly formed incentives"
- " Bad org design,"
- "Need for 'official' communication between orgs"
- "Inflexible organizations."

A perceived lack of sufficient time, budget, and requisite skills among individuals and leadership was also noted (for example: "identifying leaders able to recognize and mitigate discipline biases").

Discussion

In this section I look across all survey responses to gain a more comprehensive perspective of the first-order findings from the survey. Table 2 presents a summary of the meta-themes that emerged from the responses.

Table 2: Meta-Themes from the Survey

Q1: Importance	Q2: Benefits	Q3: Negatives	Q4: Encourages	Q5: Obstacles
Very High, Critical	System Improvements	Difficulties in Implementation related to:	Social	Social
	Cognitive Improvements	1) Confusion/ Coordination,	Organizational	Organizational
		2) Communication,		Time/Cost
		3) Conflict and Discomfort,		Skills
		4) Impacts to and from the single disciplines		

Purposefully, the survey instrument used open-ended questions rather than multiple-choice responses. Though the latter allows for more quantitative results, the former provided an opportunity for participants to speak freely with minimal prompting, allowing for a greater diversity of responses. In this scenario, consistency of responses increases the validity of the findings. For example, there were several surprises in the survey data resulting from the consistency of unexpected responses as well as from a lack of expected responses: 1) the consistency of strong responses regarding the high importance of interdisciplinary interactions; 2) responses related to social science aspects exceeded the responses related to engineering or mechanical aspects by an extremely wide margin; and, 3) the dearth of responses related to commonly used integration functions such as MDO, systems analysis, SE, and the role of a chief engineer.

The first finding noted suggests that interdisciplinary interactions are highly valued among the diverse survey respondents.   These leads to the follow up question of: *why?* Responses from question 2 helped to illuminate some of the rationale for the

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consistency of responses in question 1. Further study was incorporated in the interviews and ethnography.

The second surprise from the data is significant: perceptions regarding interdisciplinary interactions in engineering R&D are more related to social science aspects than engineering aspects. An indicator is the preponderance of responses related to interrelationships between people: conflicts, coordination, relationships, proximity to colleagues, understanding others, teaming, group dynamics, interactive activities, and the most commonly referenced topics of communication and language.

Unexpectedly, the referenced interrelation topics were not about interfaces with mathematical models, software, or hardware. These latter topics are more familiar to engineers, and a more quantitatively designed survey with prescribed, multiple-choice answers would likely have focused responses toward to mathematical models, software, and hardware interface challenges. Although answers regarding these types of engineering interface challenges would yield important data, it would also have created a significant blind spot in the data regarding topics most important to practicing engineers. Because the motivation for this study is to better understand interdisciplinary interactions with a goal of improving practice and the resulting system designs, uncovering the realities of practice is central to achieving the study goals.

The sense of personal discomfort with interdisciplinary interactions appears laced through many of the responses related to confusion, conflict, communication challenges, career impacts, negative emotions, additional time and effort, and addressing organizational and individual culture. In particular, "communication", the most commonly referenced topic of the entire survey may indicate challenges associated with ambiguity or confusion and lack of understanding due to the existence of equivocal interpretations of the information at hand. In the subsequent data that was gathered, respondents were probed in order to better delineate the source of the communication difficulties.

"Culture" was also noted repeatedly in the context of both individuals and organizations. Culture was often noted as a means of fostering as well as impeding interdisciplinary interactions. In considering the meta-themes from the survey as shown in Table 2, many of these meta-themes are inherently dependent upon or derived from

organizational culture. A deeper analysis of organization culture was initiated after the survey, the results of which appear in the next chapter.

Reviewing all of the responses, one over-arching story emerging from the survey suggests that interdisciplinary interactions are perceived as "messy" and uncomfortable to implement, resulting in a focus on social topics. What may be driving the perceived "messiness" and discomfort?

The focus on human interfaces more so than engineering interfaces may relate to the third unexpected finding: Only 3 responses (from all questions, from all respondents) referenced widely used engineering integration functions. This finding was identified from the nearly complete absence of survey responses related to these commonly used integration functions. This might suggest that these traditional integration functions may not address the social and organizational aspects noted in the survey responses. The absence of this expected response led to the development of a question during the interviews to further probe for more information.

As aforementioned, the survey was completed prior to the interview portion of the study. These provisional findings were then used to evolve the study design including the interview design and focusing ethnographic observations and informal interviews in the field. All subsequent analysis herein incorporates the first-order survey findings in a synthesized second-order analysis that includes all data obtained. Since aspects of organization culture was key element of the survey findings and a foundational element of the synthesized findings, I will begin the discussion on the synthesized findings with the analysis of organizational culture as it relates to cross-disciplinary interactions in R&D and early design of LaCES.

Chapter 4: Underlying Organization Culture

Summary

An organization's culture greatly shapes it work; as such, an understanding of the culture of working in R&D and early design in LaCES is a foundational element of this study. This chapter summarizes key elements of organization culture as they relate to the study questions based on data from interviews and ethnography. This descriptive account is provided to better understand some of the underlying drivers for interdisciplinary practices and perspectives and thus focuses on deep description and analysis of relevant aspects of organization culture rather than an exhaustive or evaluative discussion. The analysis reveals two primary cultures that dominate the work from basic research through early conceptual design: one that values physics-oriented, single-discipline focused research and one that values design-oriented, capability-focused research, the latter of which requires working with multiple disciplines. Accordingly, all respondents also articulated that both single discipline and cross-discipline work are necessary at Kappa. The two principal cultures largely share the same incentive system and organizational structure and processes, all of which favor single discipline research. Similar to the survey respondents, Kappa's leaders genuinely appear to highly value interdisciplinary engineering and appreciate some of the corresponding benefits. However, Kappa struggles with effective implementation of interdisciplinary interactions in research through conceptual design work. While its leaders may value interdisciplinarity, little is done to consistently foster it, leaving great variability in the success and efficiency of interdisciplinary efforts. All respondents were also uncertain as to who had the responsibility for connecting technical disciplines at Kappa.

To expand upon these findings, this chapter begins with an introduction summarizing the basic tenets of organization culture found in the literature, followed by sections that address the identified prevailing culture, values and lack of consistent support, uncertainty about roles and responsibility, incentives, and a description of the

two identified sub-cultures. This chapter closes with a discussion section that reconnects the findings on organization culture with the research questions, and provides a contrastive analysis of the elements of culture identified in the study.

Introduction

While definitions of organization culture vary in the literature, several key constructs are common among researchers. These constructs include values, assumptions, and behavioral norms that define the way in which an organization conducts its business.[111-113] O'Reilly, et al note that "basic values may be thought of as internalized normative beliefs that can guide behavior."[112] Though members of the organization may change, an organization's culture often persists over time since members tend to teach the culture to new members and reward those that abide by the norms.[113]

Though it is common for organization culture to be referred to in the singular, all organizations have multiple cultures, some of which may be conflicting.[113] The different cultures may be associated with different functional groups or geographic locations. For large and geographically dispersed organizations, potentially hundreds of different cultures may reside within the organization.[113]

In defining Kappa's culture for this study, data from interviews, ethnography, and organizational documentation (such as organization charts, goals, etc.) were used. Applying the constructs of organization culture commonly found in the literature, I defined organization culture by asking the following questions:
- To ascertain values:
    - What is personally or socially preferable?
    - What are shared symbolic systems that serve as criteria or standards for selection of alternatives?
    - What are enduring beliefs?
- To ascertain assumptions:
    - What is fundamentally assumed?
- To ascertain behavioral norms:

- What are group behavioral expectations?
- How are employees expected to conduct their work?

Prevailing Culture

Given its size, layers of structure, and geographic dispersion, Kappa is like most other organizations that work on LaCES for it encompasses many cultures. However, one overarching culture pervades the organization with two principal sub-cultures that appear to govern the engineering work from research through conceptual design. The over-arching culture is simply: excellence in science and engineering. Scientists and engineers at Kappa are expected to conduct their work such that they are among the best in the world in their domain areas. While this behavioral expectation appears daunting, many employees come to and remain at Kappa based on its reputation for excellence in engineering and to engage in the extremely challenging and inspirational work on which Kappa thrives.

At times, Kappa employees can take this prevailing culture to an extreme, where employees will joke of "analysis paralysis" (meaning lengthy and detailed analyses greatly slowing or impeding progress) or "polishing the apple" (meaning working to the point of diminishing returns). Other aspects of the culture of high technical excellence include positive attributes such as boldness in setting engineering goals and the passion with which employees will rally behind these goals. Negative attributes include high egos and turf battles for resources and recognition. Kappa's record of accomplishments is evidence of its prevailing culture — many within and outside the industry consider Kappa's work in science and engineering to be exceptional.

However, as described in the previous chapter, Kappa is quite similar to other organizations that work in LaCES, wherein it greatly struggles with inefficiencies both in time to develop a system and costs that often exceed original estimates by a significant margin. The high technical risks and related expensive R&D required to enable a successful LaCES, combined with a culture of high excellence, drive expenses extremely high and development timelines extremely long. And, like other LaCES organizations, Kappa has endured very costly failures of some of its systems, though a

great many are successfully and brilliantly delivered despite the extraordinary risks of failure. Looking ahead, Kappa's leaders are painfully cognizant of the need to improve efficiency while maintaining its technical quality and even increasing its innovation in order to meet increasing technical demands for its future systems.

Kappa's culture of technical excellence also pervades its teamwork, where employees will make concerted efforts to help fellow colleagues reach their technical best. Similarly, the expectation at Kappa is that if a team or person does not have high quality engineering expertise for an endeavor, then proactive measures will be taken to locate and employ respected talent through funding external participants.

The influence of this prevailing culture on the study findings is expectedly extensive. Many efforts at Kappa are focused towards securing high quality technical and physical resources, with minimal regard for the impacts of many non-engineering aspects on their work. These include the influence of organization structure or processes, including the incentive system. At Kappa, it is generally assumed that good engineering talent, sufficient technical resources including quality facilities, and dedicated time will largely enable its ambitious technological goals to be met – often with exclusivity of many other aspects. Based on its overarching culture, many leaders at Kappa assume that interactions between engineers and scientists of different disciplines will inherently occur when sufficient technical talent, resources, and time are provided. However, the study findings do not support this assumption.

While Kappa's strong success record for addressing many scientific challenges appears to support the aforementioned assumption, responses from the survey (where the majority of respondents were from other, similar technological institutions) and from the interviews within Kappa strongly suggest alternate perspectives. For example, a researcher with 25 years experience who frequently works across disciplines at Kappa repeated that he/she works across disciplines *"despite the organization."* And, a manager at another organization similar to Kappa noted that often a "sub-organization" forms that executes many of the highly complex tasks, which leads the organization's executives to falsely believe that the current organization and its processes are effective and efficient.

Hence, though Kappa leaders seem to genuinely highly desire interdisciplinary

interactions during research and early design, nearly all respondents could not identify: 1) what efforts their upper managements take to enable or foster interdisciplinarity nor 2) who is responsible for ensuring that the interactions transpire in the organization. Nearly all respondents also noted that the incentive system favored more single-discipline research. Like many research organizations, Kappa's efforts in R&D and early design are predominantly organized around traditional academic engineering disciplines such as structures, controls, fluid dynamics, etc. Respondents overwhelmingly supported the need for such an organizational structure as well as a need for interdisciplinarity. In examining the responses from the interviews and informal interviews from ethnography, it became clear that for Kappa's research through early design work, two sub-cultures also co-exist: one favoring focused research within a single discipline and one favoring focused capability development requiring multiple disciplines. Not surprisingly, the two are in tension at times in the organization – yet nearly all respondents supported the need for both types of work at Kappa.

The subsequent sections of this chapter will provide a deeper examination of some of the potential impacts of Kappa's culture on interdisciplinary interactions in research through conceptual design. The topics were chosen based on their prevalence in the responses from the interviews and ethnographic observations.

Interdisciplinarity is Valued Yet Neither Directly Encouraged Nor Intentionally Discouraged

Interdisciplinary interactions between engineers are valued at Kappa and nearly all interview respondents argued that it is necessary, similar to the survey respondents. A subsequent chapter will delve more deeply into the benefits of interdisciplinary interactions as stated by respondents. A small minority of respondents noted that working across disciplines is viewed favorably at Kappa. For example, a line manager with 25 years experience says: *"Operating across disciplines is really, I think, looked upon favorably and encouraged more so now than it has in the years past."* In ascertaining culture, initially it appeared straightforward to suggest that interdisciplinarity is of high value given the strong responses from the survey and interview respondents

and based upon organizational materials such as stated goals. However, sufficient data to the contrary challenged my earliest provisional findings.

For example, most respondents suggested a lack of proactive measures in the organization to enable the interactions. A respondent with 35 years experience states: *"I don't think [working across disciplines] has ever been encouraged for its own sake, only if we have to fit into a project or get some funding."* It appears that leaders neither directly encourage nor intentionally discourage interdisciplinarity. Table 3 displays accounts from several different respondents, each with more than 10 years experience.

Table 3: Responses From 7 Researchers, Each with more than 10 years Experience, Regarding Organizational Support for Working Across Disciplines

- *"I don't think it's discouraged. … I've never gotten a feel that that kind of cross-fertilization is discouraged but I've just never really gotten any real clear thing coming down from management that, 'This is what we want you to do. This is what we think is part of your job.'"*
- *"I don't know that I would say that our [upper management] is really doing much to help that."*
- *"I don't know that there is any active, necessarily, leader or something."*
- *"I'm not sure they're really doing things to discourage it. I'm just not sure it's that a big emphasis for them."*
- *"Oh, everybody talks about it. Everybody pays lip service to it. We should be doing more cross-disciplinary organization work. Everybody pays lip service to it, but when it comes time to implementing, what do I do?"*
- *"I think it [the organization] strongly discourages."*
- *"There's [an activity within our organization] that I think is really good. It just gets people from a lot of different parts of the lab working together. You know what, I don't know other than that, honestly what organizationally we're doing—….I don't know what the high levels—if we're really doing anything to encourage it."*

Most respondents implied that the organization had few explicit barriers against interdisciplinarity. Rather, opportunities to work across disciplines are available, and many employees avail themselves of the freedom to do so. For example, one team leader with 25 years experience noted: *"So, how the organization has helped is some extent – I've got the freedom to do it [work across disciplines]."* Another researcher with 30 years experience concurred: *"There's usually opportunities for doing cross-disciplinary work. Because you're sitting with people in different organizations that are pretty much top level, aware of what's going on in the world—top level. The opportunity is there whenever you want to seek it out or should seek it out."*

Though the opportunities exist and upper management appears to value interdisciplinarity, nearly all respondents noted that implementation of interdisciplinarity can be difficult and the effectiveness of implementation varies widely in the

organization. Further, a deeper analysis across all of the data obtained points toward several implicit barriers. One line manager summarizes a common lament held by many respondents: *"Within [our] environment, it's not very conducive to initiate interdisciplinary, cross-disciplinary research. There are too many barriers."* While several explanations are available from the interviews and ethnographic data, the strongest deterrents related to the organization may be identified as three main aspects: 1) uncertainty as to who has the responsibility for driving interactions across disciplines; 2) the incentive system; and 3) the organization's structure. Other deterrents and encouragements, not directly tied to the organization, are discussed in subsequent chapters.

Uncertainty Regarding Who is Responsible for Driving Interactions Across Disciplines

From the interview responses, it became clear that no one person or position had the responsibility to foster interdisciplinarity, leaving great variability in the productivity of the interactions. This finding is somewhat unexpected given the level of importance organizational leaders and researchers place on interdisciplinarity. While some respondents were very direct in saying that no one had the responsibility, for most respondents, this finding also emerged from what respondents did not say specifically. This is significant as most respondents were typically very explicit, particularly when probed for more specificity as was done regarding this topic. When asked who had the responsibility for interdisciplinary interactions in the organization, nearly all suggested who "should do it" or "could do it." During the interviews, I probed further by asking questions such as "Do you experience [the suggested person or role] doing this frequently?" Responses were typically equivocal, examples from five different respondents follow:

- *"Um, not explicitly,"*
- *"Sometimes,"*
- *"Some do, some don't,"*
- *"I think every level in the organization has different opportunities,"*
- *"I believe so, yes."*

All of the above responses originated from personnel with considerable seniority in the organization. Some of the less equivocal responses from five other respondents, all with more than 30 years experience, were:

- *"No, but it might be a fun job to do!"*
- *"In my experience it's always been me. It seems to be somewhat self organizing."*
- *"Nobody's [job]. Everybody's out there for the food fight protecting their turf."*
- *"That's not [the researcher's] task. They're not tasked to do integration. (Joking) So, for example if you're a [discipline 1] person, why would you want to work with the [discipline 2] guy?"*
- *"I tend to [connect different disciplines] all the time, but I don't know if they listen to me."*

These responses are primarily of interest in comparison to the suggested high importance of interdisciplinary interactions. Many respondents proposed that the people in the organization who "should" or "could" do interdisciplinary interactions were either line managers or program or project managers. However, from the data received, it appears that team leaders that reside within the line organizations were typically those conducting the cross-disciplinary interactions.

Incentive System

Based on the overwhelming response from the interviews and ethnography, the incentive system at Kappa for research through early conceptual design work appears to be focused on individual achievement, largely measured in the number of papers published. A line manager with 20 years experience describes the incentive system:

> *"That's the way the structure, the performance evaluation is structured like that. On an individual basis, what have you done? ..to get promoted, is about 'this is what I've done.' If you work in a team, then it's like, 'oh, the team did it. What did you do?' There's a big emphasis on what I have done, me individually. ... A guy who's been doing this particular area for so long, why would he want to do something else when he can convince people to give him [the resources he needs] and publish papers?"*

Responses regarding the incentive system were frequently volunteered and pointed. Many suggested that the most significant challenge is clearly identifying what an individual has done on an integrated effort. In Table 4, line managers and researchers describe the emphasis on individual accomplishment at Kappa.

Table 4 Descriptions Regarding the Individuality Emphasized in the Incentive System

Line managers (all supervisors) remarked: - *"That's the hard part, because our mindset is that everyone has to do their fair share, and I have to have a clear way of measuring and documenting a person's contributions. It is hard to identify what someone's done, but I think that's the role of the local supervisor."* - *"You're still graded on your own individual performance. That's the whole system- is grading on individual performance, not how you contributed to a team becoming better. … [the promotion process for research] encourages people to pursue their own individual thing as opposed to working in a team,"* - *"I think we still as an organization reward someone who's narrow and deep. As a researcher. Not as a Project Manager, but as a researcher."* The researchers interviewed echoed these sentiments, often describing the need to "get credit." Three researchers with greater than 20 years experience remarked: - *"One of the blocks to collaboration is—there are a lot of obvious ones, but egos are a big thing, and who's going to get credit for something. Those aspects can stand in the way, and getting credit for an idea affects people's career advancement."* - *"They're afraid that if they share what they're working on, someone is going to steal credit for their work."* - *"If I work on this, it might be a dead end and I don't get a reward, and it's very difficult for me to go through the [line manager's] evaluation process: 'What great things I did for the project? Oh, I just worked with this guy and did some studies,' and who wants a study?"*

As noted in the first-order survey analysis, the perceived benefits of interdisciplinary interactions are largely realized in the long term and are somewhat intangible, making quantitative measurement of the benefits challenging. Four respondents from different line organizations, each with over 30 years experience, mentioned the following challenges in specifying some of the intangible aspects of working across disciplines:

- *"I've got my performance review coming up. It's very hard to quantify any of this."*
- *"You mull over a topic more than you are given credit for."*
- *"It's just my general feeling is that they [the line managers] don't entirely see what I've done or know how to reward that."*
- *"The really biggest problems are that people are afraid to be exploited or used without enough credit, afraid that they'll waste too much time for no observable benefit to them."*

The upper management at Kappa frequently noted that they no longer exclusively focus on the number of papers that a researcher has written as a criterion for promotion. However, nearly all respondents clearly described the number of papers

as a critical and motivating element of the promotion process. For example, experienced team leads often commented about trying to help members of their respective teams: *"They want good topics that they can do some research and publish on. That's how they get promotions."* The influence of the incentive system is pervasive, as noted by every respondent. Table 5 provides views from three different employees in three different roles in the organization, all with over 25 years experience.

Table 5: Responses about Impacts of the Incentive System from Three Different Roles in the Organization –All from Respondents with over 25 years experience

- One single-discipline senior researcher leading a large team noted: "*[Some people say,] 'I want to work on this because I have full ownership of that, and I'm going to get recognized when I make that happen. If I work in the project, I might not get recognized for it because I'm part of a big team.' I mean you might get a team award, but that's not a promotion. It's just a team award. And they like that, but they also want to get recognition, and if we only go by what an individual does to allow him to be internationally recognized type thing, published in the journals, etc., he needs to focus on his work.*"
- One senior researcher working in systems analysis, who strongly favors interdiscipline research and self-identified as "an integrator," summed up Kappa's work as follows: "*Our research products are much more discrete. They don't naturally integrate. We do a piece of research. We write a paper. We publish. That's our work product. Our product isn't then to take that and integrate it with somebody else necessarily. We've accomplished the thing that we're charged to do. We've done our research. We've documented it and now we can go on to our next bit of research.*"
- From a line manager: "*Internally, there has to be—line management wise, there has to be some incentivization of cross-disciplinary research. You've got to promote people who are good at working with others, not just who … publish papers. ..it seems like the promotion is looked at by the senior technologists who got there by publishing papers. They don't work with anybody. They're just individual contributors. … They publish a lot of papers, and they're the ones who are evaluating people to get promoted. They're going to promote people like them. … People want to publish their own papers so that they can get promoted. Working in a team doesn't help them get promoted. There's almost a de-incentivization of trying to work in a team.*"

The incentive system along with the lack of clarity regarding what organizational role is responsible for leading cross-disciplinary interactions both create explicit and implicit barriers to effective implementation, though Kappa leaders and employees argue that the interactions across disciplines are important for meeting their scientific goals. Another important organizational influence is the structure of the organization. This will be discussed in a subsequent chapter.

While comments regarding the single-discipline, single-researcher incentive system were strong, originating from nearly all respondents, many comments were flavored with enough positive and negative emotion to warrant closer scrutiny. For example, sarcasm or apparent frustration was noted as well as an upbeat and enthusiastic view regarding work across disciplines. Evidence of a second sub-culture

at Kappa began to emerge from carefully re-listening to and analyzing the interview data and seeking additional input through informal ethnographic discussions.

Two Sub-Cultures Regarding Interdisciplinarity

In re-examining significant portions of the data to discern the meaning behind many of the remarks, it became clear that Kappa essentially has two dominant sub-cultures that co-exist with some tension. One of these cultures values single-discipline research more focused on physics-based understanding of scientific phenomena. The other culture values multiple-discipline research more focused on design-based development of new capabilities. The work of the two cultures overlaps and is necessarily highly interdependent. Nearly all respondents noted that the work of both cultures is needed at Kappa, though the incentive system appears to favor the culture of single-discipline research.

In this section, I provide a table summarizing differentiating aspects of the two cultures (Table 6). This high-level contrastive summary provides a descriptive account to frame subsequent discussions in this study, recognizing that the boundaries between the two cultures are indistinct. Hence, this summary should not be viewed as either exhaustive or exclusive. Supporting interview data based on vignettes from respondents will follow in the discussion section.

In general, the higher engineering goal of both cultures is the same, expressed by one MDO researcher with 30 years experience as: *"motivated by improving the system or making something [operate], making it safer for people, making it better for the economy or making it [better for the environment]."* The principal difference is approach towards this end.

Table 6: Summary of Two Interdependent Sub-Cultures (Source: the Author)

	Physics-Oriented, Single-Discipline-Focused Research	Design-Oriented, Capability-Focused Research
Values: Enduring Beliefs	Focus is within a discipline	Focus is on using discipline knowledge for a concept that requires multiple disciplines
	Deep understanding and analysis of phenomena within a discipline	Creating a new system capability which is sometimes focused on solving a system problem
Values: Shared Symbolic Systems for Decision Making Criteria	Technical papers	Difficulty, novelty, or potential benefit of the new capability or problem solved
	Demonstrated level of understanding of the physics of a phenomenon	Demonstration of the capability or solved problem
	External recognition within one's technical area/ discipline	External recognition by potential users
Assumptions	Among the international leaders in technical understanding within a discipline area	Among the international leaders in system or subsystem capability
	The journey toward understanding and analysis is beneficial regardless of the ultimate research outcome	The journey toward developing the new capability or solving the problem is beneficial regardless of the ultimate research outcome
Behavioral Norms	Whether working internally or externally, conduct the work individually or in small groups largely within a single discipline	Work with the requisite disciplines internally or externally to enable a viable system, sub-system, technology or capability or problem resolution
	Seeking improvements within the discipline	Seeking improvements for a system, sub-system, or integrated technology
Synopsizing Concept-ualization	Analysts	Designers
	Understand and improve the "leaf or tree"	Understand and improve part of or the entire "forest or ecosystem"
	Inspired to produce "academic" products such as validated theories, reference-able results, and computer simulations within the discipline	Inspired to produce "design shop"-like products such as creating breakthrough system capabilities, innovations, or integrated technologies
	Interdependency with the design-oriented sub-culture: - Guided by the needs of the "forest" - Goals are pruned to be more independent, such as focusing on type of "leaf or tree in one type of environment"	Interdependency with the physics-oriented sub-culture: - Built upon a deep understanding of the "leaves and trees" by themselves or others. - Goals are nurtured to understand the "forest's interdependencies in many environments, such as decay to enable growth in swamps, meadows, or a larger ecosystem."

The existence of the two sub-cultures was apparent in numerous responses. One respondent, a researcher with over 30 years experience who prefers single-discipline research, provided a vignette (shown in Figure 4) of his/her work in his/her line organization where the two cultures sometimes collided. This vignette illustrates several points: how the two cultures intersect and rely upon each other; even within the

same workgroup researchers from the different cultures do not always respect the work of the other; and line management can have a significant impact on the direction of work within a group.

"My [line manager] at the time, 'Oh, no, no, we're not—we have to understand [physics of every piece] and little [fundamental experiments] and stuff, and we're not going to do that.[a systems-like experiment]' … I was willing to try to design a [larger experiment that encompassed multiple phenomena], recognizing that yes, we still need to do fundamental [research of specific phenomenon]. ... So, sometimes a narrowly focused research approach in a technical [line organization] might keep you from doing both. We have people in my [line organization] who are very focused on understanding every detail. They'll make statements like 'we won't' understand [the detailed physics], even on small experiments for 20 years,' and that may be true. On the other hand, [we] need to design today for [practical applications that are already in use]. So, you need to do both. … The work [with larger experiments with multiple phenomena] I've led has at times been frowned upon because it's not fundamental enough. If you don't support what's happening in [real applications], the question is will you ever be relevant? In 20 years you might have that small [experiment] totally figured out, but there have been maybe three generations of [real applications] and the opportunity's passed you by. … So, it's so much more relevant than just doing small [experiments], but I'm not critical of small [experiments] because some of the physics we don't understand by jumping to more practical applications will be developed from very carefully looking at small [experiments]. So, I really feel you need both. … But, there's just been resistance in the past… People in my [line organization] were sympathetic to the work we're doing and see the relevance of working with real [systems] with [potential users], because we are willing to do that before we understand every bit of the physics about small [experiments]. They would actually look down their noses at people doing pure fundamental research, because we can write thousands of journal papers over many, many years and spend a lot of money. How does it really help our industry be competitive? That's one view, but the technical people [who focus on high fidelity physical level understanding] don't see it that way. They think that those very detailed journal papers are very important. So adding a fifth and sixth order term to a differential equation gets you a two percent better result, technical researchers think that's great stuff. Some people think, well what a waste. If you're already getting a 95 and 97 percent answer, why are you wasting money doing that?"

Figure 4 A Vignette From a Single-Discipline Researcher with 35 years experience Illustrating how the two cultures can reside in one line organization

Responses from other respondents regarding the two cultures are provided in Table 7. In this table, respondents describe the existence of two cultures and the need for both cultures. The respondents note that working across disciplines and within one-

discipline is not best described as "either-or" but more as "both-and," where researchers must address the varying needs of the broader organization by balancing both single discipline and cross-discipline needs while keeping the needs of their careers, their line manager, and their project in mind.

Table 7: Examples of the Two Sub-Cultures From Four Respondents in Four Different Line Organizations

Single-Discipline Researchers in Two Different Line Organizations, both with over 27 years experience:
- *"You have [local organizational] interest, … which a lot of this is about keeping capabilities and stuff in your area, which I think you should do. Because if you lose expertise, then you can't respond to project needs either. There's a little balancing act that goes on, I think."*
- *"You need a combination of the depth people and then the translators that look across well enough that they can make the connections and then let the depth people kind of come back up to the surface a little bit to be able to talk to other people at the surface. Then they go back down into their holes."*

Line Managers, both with over 25 years experience (these managers do not supervise the above employees):
- *"I think sometimes the line managers have a lot to do with whether or not—if a line manager is the person who has a certain perspective or viewpoint of how research should be done, they may be a plug in the system. They may not be a proponent of getting lots of people together. So, you have your overall culture, but then you have your individual organizational culture. If your organizational culture says, okay, I have to work alone because my ability to be promoted is all based on the work that I do and the recognition I receive, then you may not be willing to spend time working with other people because you don't feel that that's going to be as rewarding for your career."*

- *So I don't think it's anybody with bad intentions, it's just different—what you're after. People here are after physics, basic understanding. The Projects have to go to [their stakeholders] and say, this is what we're doing and how it benefits the [greater goals]. So it's kind of a fundamental disconnect, and you just have to meet in the middle sometimes. …[In cross-disciplinary work you] gain a broader view of what the real problems are to overcome. Say for example they have ideas of how to improve some small thing that's within their main discipline, they'd get a better view of how could you actually bring that to fruition in a real application."*

Expressions of Frustration and Fun

In this section I look at other aspects of organization cultural values in terms of what is personally or socially preferable. Many in the organization genuinely prefer working across disciplines. This preference was expressed in terms of frustration and fun – frustration due to having to work through some of the obstacles previously mentioned and fun due to the learning and discovery inherent in the work.

Though nearly all respondents appreciated both aspects of Kappa's work, several respondents alluded to leadership at times favoring physics-based, more single-

discipline research or simply not providing sufficient support, appreciation, or incentives for doing cross-discipline research. The existence of the two cultures at times created a tension in the organization with some frustrated by a lack of support for cross-discipline research. Those in the organization who work more toward the conceptual design end of the spectrum universally expressed frustration in implementing cross-disciplinary research at Kappa. Table 8 depicts expressions of frustrations from single-discipline researchers and systems analysts, the latter of whom work largely on early conceptual design.

Table 8: Expressions of Frustrations

Two Single-Discipline Researchers (with over 20 Years Experience) who are Leading Large Cross-Disciplinary Teams:
- *"They [the team members] have to show... how [their work] is connected to the ... goals and why this is important to do, and if you succeed, does anybody care? Or is it just something that allows you to get a publication in a journal? It's good for you, but it doesn't do anything to meet the [organization's] goals of [system level improvements]? ...People somehow seem to think it's just a research lab. We're going to just do research because I can get a publication. Unfortunately, that's how they get promoted, so there's a catch-22. ... May be contributing very well there, but it never realizes itself into a real product if you will, or enabling future products. A lot of people just write papers to go to conferences or to get promoted. I wish we could find a different way to do that."*
- *"It's just my general feeling is that they [management] don't entirely see what I've done or know how to reward that. ... I think I make my own rewards. I've learned to see—I enjoy the interactions with the people and to me a reward is seeing these [discipline 1] people and these [discipline 2] people who are complete polar opposites and different worlds, and seeing them coming together, and both of them afterwards independently saying, 'Wow, that was really valuable.' That to me is a reward. It's an intangible. It would be nice—I think I get some recognition. I don't think the line management knows what to do with me. ... It's just my general feeling is that they don't entirely see what I've done or know how to reward that. The line management, don't get me wrong, they've been supportive and they've said ... 'Yeah, you're doing a great job,' So, I think that their view of what I'm doing, they don't appreciate the level and the depth of what—and I can't say that I've accomplished yet, but what I'm forming. ...at the project level, I think that they're finally appreciating that and saying yes, this is what we want. So, I think that the project all along has wanted and craved that interdisciplinarity, but they didn't know how to do it."*

Three Systems Analysts (with over 30 Years Experience) who Largely do Early Conceptual Design Related Work:
- *"[Working across disciplines] has to be not only just looked at favorably but it has to be, 'You haven't finished. Yes, that's all very interesting. That's all well and good. That was a great paper. You know, congratulations on getting accepted to the journal but how did you make our system ... better?'"*
- *"The majority of them don't care whether what they're working on ever winds up [being used on a real system] or not. They're just happy to hunker down and do their thing. They get some sort of self-satisfaction of—here's my prejudice coming in—oh, they get to publish and go to this conference and that conference, and their colleagues all applauded when they were done. ... Most of the [managers] have come up through the ranks with the same sort of thinking. Our whole [organization] is sort of built around research and paper publishing, 'Oh, you got best paper for the year.' That's something. ...They don't value the same things that we value, that I value, in [my part of the] organization of having an impact on the world, on our product, on what we do. Maybe they do."*
- *"The old-style [way of doing things around here] says you do an experiment, you do the analysis, and they match and you put your little chart up there. Done. Well, a lot of this multidisciplinary stuff, doing*

the experiment to prove that the analysis is right is just really difficult or expensive or hard to pull together and so that's why when you present just the analysis part [of the multidisciplinary work] you get no respect. …You can do a simple little [coupon-like] test and explain to your boss that, 'Well, we could make the whole [system]—if you wanted the whole [system],' but you don't. Whereas it's hard to come up with a [coupon-like] test that proves that our [cross-disciplinary] conceptual design is working."

While frustrations in implementing cross-discipline research are clearly high among some at Kappa, many respondents also expressed that they deeply enjoy working across disciplines. Given the prevailing culture that values excellence in science and engineering, many employees at Kappa earnestly seek to expand their knowledge and capabilities. During the interviews respondents were never directly asked if they enjoy working across disciplines; however, many respondents offered positive descriptors of their work when it involved other disciplines. Table 9 captures expressions of fun and enjoyment from several respondents. In Chapter 7 I explore other positive opportunities afforded by working across disciplines. In general, respondents noted that they enjoy the learning, creativity, discovery, and exploration aspects of cross-disciplinary work. The significance of this finding is that many significant barriers to cross-disciplinary work were identified in this study including career implications, communication issues, social challenges, organizational confusion, etc. However, in spite of these challenges, many researchers, team leaders, and some line managers are still drawn to this type of work, deeply valuing it and sincerely enjoying it. Hence, the culture may not fully support working across disciplines, but many employees are still internally motivated to pursue it none-the-less.

Table 9: Positive Expressions of Enjoying Cross-Discipline Work

Single-Discipline Researchers with over 20 years experience: - *"I think it's also interesting from the point of view that you learn different things and you don't get static. Most engineers want to keep learning and we're curious about things by nature. So, it kind of keeps things from getting too stale."*   - *"So, to me, my frustration was born out of being stuck in the stovepipe. So, for me I find it exhilarating and almost a release to be able to learn something, enough about these other disciplines that I can, I guess, maybe be a translator. … [A researcher in another discipline will say] 'Boy, this has opened up a whole new area of research for me.' [Researchers are saying] 'This is so exciting!' I think it's partially because.. they're seeing some freedom and some interdisciplinary connections that they've been craving. …They're the ones on the edge of their seats, and they're the ones that are engaged, … There's something there that they're excited about or they're engaged about …So, I think that everybody goes back out, and they work on their own little thing, and they come back in, and they're so*

energized, and they say, 'Look what I did.' It really is infectious. ... So, I think part of it is it's fun. We have fun."

- "I've been working with this group [from another discipline] and it's been fun from the point of view that I've realized, is that when you want to make a better [system], and that's the ultimate goal.... To get to that goal, [the other discipline] wants to do certain things, but those certain things will certainly affect [my discipline]. ... I've enjoyed that part of it, of realizing that [the other discipline's goals] are a good thing [also]."

- "I am actually finding I enjoy this to some degree because I feel like I'm earning my pay better than just writing journal papers. I'm having a better impact."

MDO Researchers or Systems Analysts with over 30 years experience:

- "When you're at the [capability-development] side it's just so wonderful when you do cross disciplines because you get all the help you can get and everything is so fulfilling....People really sort of identify this is one of the critical issues to make something happen, or this is the barrier for the next step. ...It was a really great five years. I thought it was the end of my fun year, but then we suddenly have this [extension of the work] and doing joint design work and all kind of interesting stuff."

- "I love it. You're always learning something new. I mean you never get bored. Yeah, I think it's a lot of fun."

- "Actually, in that particular project, that was another one where I was working with a really good design engineer. He could draw up [my ideas] and he was having ideas on his own at the same time. That was a really fun collaboration."

- "You make this my job; I'd be the happiest guy in the world."

Cross-Disciplinary Research - Misnomer or Interdependency?

Another influential aspect of Kappa's culture is the assumption by some that research is inherently single-discipline such that the term "cross-discipline research," appears to be somewhat of a misnomer to some, including the leaders. Some respondents distinguished "research" from "engineering", for example. Below are three example excerpts from interviews and ethnography:

- An executive: *"Basic research is single-discipline. That's just the way it is."*
- A senior researcher: *"Our methods are more engineering oriented than real theoretical oriented."*
- A line manager: *"They're engineers, more so than researchers."*

The assumption by some that cross-disciplinary work is not "research" results in some of the frustrations noted earlier. Several self-identified system thinkers frequently expressed frustration in working at Kappa, where they felt their colleagues and leadership did not appreciate nor value their work and non-traditional skills.

The above respondents who did not consider cross-disciplinary work to be equivalent to research were counterbalanced with numerous respondents who carefully described cross-disciplinary efforts as research and noted the interdependency of basic,

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single-discipline research with design-focused cross-disciplinary research. The consistent message from the respondents, that both types of work are needed and that each is dependent upon the other, resulted in a key finding of this study. The finding is: for LaCES R&D and conceptual design, physics-oriented single-discipline research must work with design-oriented capability focused research and vice versa. One is ineffective and inefficient without the other. As noted previously, the organization's structure also has a significant impact on the culture of the organization and resulting work of the employees. This will be presented in a subsequent chapter.

Discussion

In this section, the findings regarding organization culture will be discussed by reorienting the discussion back to the research questions and other organizations similar to Kappa to provide greater transferability of the findings beyond the context of the study. In this study I endeavored to understand *how* the organization, its people and processes, intersected with the needs of the engineering product to influence *how and why interdisciplinary interactions are accomplished.* An examination of organization culture provides a necessary element in discerning the rationale behind an organization's interactions.

This study is focused on a wide span of work that includes basic research and development through early conceptual design. With the need to foster both high physics-based competence and high design-based competence in the same organization and the need to enable the two areas of competence to work together, Kappa and similar organizations inherently have both competing and complimentary values within the organization, yet with a single predominant incentive system. The yin and yang of the two areas is expressed by a senior researcher with 30 years experience as:

> "On one hand it's very stimulating getting to interact with a lot of people and work outside of your area. On another hand, some problems you just need to spend a concentrated amount of effort really focusing for a while on something... To really push hard and deep… and make some breakthroughs on a particularly hard subject – you may need to spend several weeks at your desk without being bothered… On the other hand, if you've beat your head bloody on

the wall maybe you ought to go out… and see other things and maybe a new idea will pop in. That's a back and forth thing."

Examining Kappa's culture from a wide view, it is apparent that the prevailing culture of high technical competence, as well as the two sub-cultures, has endured at Kappa for a considerable time. Corporate memory is also very long at Kappa, given the many long-term employees. Many employees will talk of "how things used to be" which may refer to corporate actions 15 years to as many as 40 years in the past. Thus, Kappa's cultures are likely tacitly and explicitly taught to new employees.

While Kappa's cultures are slow to change, many long-term employees noted that Kappa's work has evolved in several aspects, notably:

1) Funding being controlled by projects rather than by single-discipline line organizations (this change occurred in the mid 1990's);

2) The entrance of a younger, more socially networked generation who seek to work in a more networked fashion;

3) The organization's goals becoming increasingly multidiscipline, interdependent, or system-focused;

4) The organization's work requiring larger teams that are geographically-dispersed; and

5) The technological options within a discipline or system continue to grow significantly and rapidly. This expanding and rapid technology growth makes keeping abreast of, and on top of, advances in a domain area a challenge for the single-discipline researcher; and it adds an enormous sea of possibilities for the capability-focused researcher. For the latter, this sea of possibilities is likely too large to fully assess for all relevant disciplines required to develop a capability, resulting in most respondents relying upon their network of colleagues and their own experience to identify technological options.

Each of the changes identified above likely has significant influence on the work and culture at Kappa that may include important aspects such as social, intellectual, leadership, knowledge transfer, communication, hiring, incentivizing, and job design. Several of these aspects will be discussed in the chapters that follow. However, an in-

depth study of each change warrants further study beyond the scope of the current work.

From the perspective of a researcher at Kappa, work in a cross-discipline area represents a difficult choice. Some of the potential considerations are delineated in Table 10. Here 'cross-discipline researcher' does not connote a generalist necessarily. Rather, it is a researcher who considers more than one discipline in their research, with varying levels of depth in the other discipline(s). For example, a researcher may spend as little as 10% of their time with another discipline or 90% of their time with other disciplines – or may enmesh themselves in another discipline for a specific time period to address a certain project, then return to research in their discipline.

Table 10: Potential Career Considerations for a Researcher

Competition and Advancement Within and External to Their Home Organization	Cross-discipline researchers will likely never out-publish their single-discipline counterparts, but they likely lay groundwork for their counterparts to publish in their domain areas.
	Cross-discipline researchers will not develop depth of knowledge on par with their single-discipline counterparts in a domain area, but will develop depth of knowledge on the connection between domains and how to integrate domains to improve a system.
	Cross-discipline researchers improve systems-thinking skills, yet these skills may be more difficult to demonstrate tangibly.
Delayed Reward	They can publish their work more quickly working in a single discipline.
	Often it takes additional time (noted by many respondents) to accomplish something "publishable" by conventional means when working across disciplines.
Less Control of and Difficulty in Measuring Progress	It takes several weeks or months at the beginning of a new cross-discipline effort to work out numerous cross-discipline challenges (team formation, communication, etc.)
	The cross-discipline process appears clumsier and not as straightforward (clear, linear, and stepwise) as the single- discipline process that appears more controllable and known.
	An individual contribution is more difficult to identify.
Delayed feedback and attention	They may obtain more individualized attention and accolades via keynote addresses, best paper awards, journal publications, etc., when they work in a single-discipline area.

In summary, though Kappa's culture welcomes cross-disciplinary research in some regard, implementing this research also challenges the existing culture, which rewards more single-disciplinary research and individual sovereignty. Respondents expressed both frustrations and experiences of rewarding work often described as "fun" in conducting research across disciplines. While Kappa's leaders and managers and its

stated organizational goals appear to support cross-discipline work, the lack of a clear organizational role that has responsibility for orchestrating the work and lack of clear upper management support result in great variability in the consistency, effectiveness, and efficiency of cross-disciplinary research.

Chapter 5: Cross-Disciplinary Practices and Perspectives

Summary

An explanatory framework is presented as a means of delineating several constructs of working across different disciplines in R&D and early design of large systems. The constructs are: 1) four of the primary methods of combining disciplines; 2) two over-arching paradigms regarding system characteristics; and 3) a single-discipline as a system. The four primary methods of combining disciplines are presented first as a baseline framework from which to enhance understanding of the other constructs. In this framework, the four methods are conceptualized as Connection, Coordination, Collaboration, and a Collective (the 4C's of Combining System Elements). Discussion regarding challenges and opportunities for leadership, management, and communication are presented.

The 4C's also provide a means to depict two overlapping principal paradigms regarding system behavior that drive cross-disciplinary practice. One of the two paradigms concentrates on understanding the system as a more modular combination of different elements and the other focuses on understanding the system as a more complex combination of interdependent elements. The final construct described in this chapter is the cross-disciplinary approach of used by many respondents where a single-discipline was the primary focus of the cross-disciplinary interactions. This practice tends toward combining disciplines for a micro-system (a single-discipline analysis or concept) rather than for a macro large-scale engineered system that encompasses many disciplines. The three constructs presented in this chapter summarize the central practices and perspectives on cross-disciplinary interactions that emerged from this research. In all cases, the practices and perspectives are distinct but not fully separable, for they overlap and interact. Contrastive analyses are used for increased clarity only.

Introduction

The literature includes numerous constructs or frameworks for examining cross-disciplinary practice in a variety of settings (e.g., academia, small businesses) for an array of different purposes (e.g., learning, product design).[6, 13, 17, 46, 114]   As aforementioned, the focus of this work is on cross-disciplinary R&D in large, dispersed organizations as a precursor to the design of large engineered systems. While the R&D work takes place across many buildings and geographic locations among hundreds of employees, the R&D efforts are intangibly linked to an ultimate system. In practice, respondents described many means of working across disciplines, from very little interaction with other disciplines to continuous interaction.

In this chapter, I present the four most common methods of interacting across disciplines in R&D and early design based on the empirical data obtained. These methods also depict two other important facets of this study: 1) the two predominant paradigms on combining disciplines and 2) methods used when a single-discipline (rather than an engineered system) is the focus of the interactions across disciplines. The different conceptualizations, particularly the 4C's of Combining System Elements, are best viewed as explanatory frameworks that describe, illuminate, and clarify practices and perspectives, rather than categorization frameworks that classify and structure practice. As such, the conceptualizations describe practices and perspectives that overlap as well as interact. They are presented separately and contrasted purely for analytic clarity and convenience.   The discussion of the explanatory conceptualizations is also complicated by the fact that our language implies an ontological separation when this is neither warranted nor intended.   The recursive relationship between the descriptions should be continually borne in mind.

In addition, I note these findings are neither exhaustive nor exclusive to other potential findings, but rather they represent the most predominant constructs that emerged from the data gathered. It is hoped that the descriptive nature of these findings provides a rubric of sorts to improve understanding of current practice and guides further study and improvements to practice. Some considerations for further study are highlighted throughout the text. For all descriptions herein, the following

terminology will be used:

- System: refers to the focus of the integration effort whether it is at a macro level (an aircraft), or at a micro level (a technology), or something less tangible (a network)

- Element: refers to what is being integrated into the system whether it is physical hardware (wings, metal beams), or software (mathematical models, computer programs), or the (less tangible) capabilities an individual brings to a cross-discipline team such as disciplinary knowledge, expertise, ideas, creativity, training, culture, etc. In all cases, the aforementioned different types of elements represent aspects that may be combined into a system.

Four Primary Methods of Combining Elements in Cross-Disciplinary Work

In taking a wide view of the integrated data, four distinct forms of combining elements from different disciplines in LaCES R&D and early design were discerned. These are conceptualized as: Connection, Coordination, Collaboration, and a Collective (the 4C's of Combining System Elements). The last concept, called a collective, is unique and less understood by many respondents, many of whom were not aware they were operating in this manner. Accordingly, additional discussion is allotted to this concept. The conceptualizations of the 4C's were primarily developed based on ethnographic data, with many examples from interview data as well. The methods are presented separately for clarity; however, in practice, these methods are used simultaneously and to varying degrees during different stages of R&D and early design.

The significance of these four methods of working across disciplines is that each method embodies assumptions about how the elements of the cross-disciplinary effort are combined. For example, each method has differences in engineering aspects such as:

- The frequency and depth of interactions;
- The expectations about the inclusion of previously developed concepts; and
- The level of specificity needed regarding the final system.

In social and organizational aspects, each method also presents differences in:

- The proximity of the work group (degree of co-location or lack of a need for proximity);
- The cognitive challenges on the participants; and
- The social connections or relationships that are needed, etc.

Interestingly however, very rarely were these differences clarified in practice, because most respondents were not cognizant of the differences themselves. Nearly all respondents appeared to have clarity on the goal of their interactions with other disciplines yet lacked clarity on the different methods by which to do so. The variations in the four methods of practice, if not clarified, likely cause some of the confusion, frustration, and inefficiencies noted by some respondents.

In creating these four conceptualizations of cross-disciplinary methods, I endeavored to capture salient aspects of the most commonly described practices. The respondents themselves were not consistent in their use of the four terms chosen; however, they were largely consistent in their descriptions. Descriptions from many respondents and data from ethnography were used to create these conceptualizations. Figure 5 provides as a graphical depiction of the four methods and Table 11 provides a comparative summary of the principal characteristics of each method.
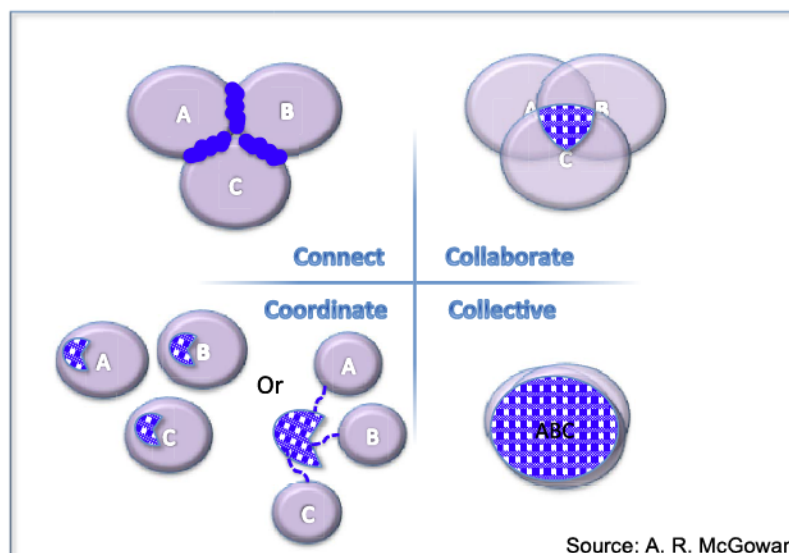
Figure 5 Graphical Depictions of the Four Primary Methods of Combining Disciplines in a System

Table 11 Comparative Summary of Principal Characteristics of the Four Methods of Combining Disciplines (Source: the Author)

Connecting	Coordinating	Collaborating	Collective
Connecting separately developed elements into a system	Integrating user needs to create a common or shared artifact. This multi-user artifact is the system.	Creating a heterogeneous combination using aspects of different elements	Creating a homogeneous mixture or solution from different elements.
Elements used to develop the system are generally tangible articles or components of physical or cyber hardware, software, mathematical models, etc.	The elements of the system are diverse user needs. While the users may or may not physically connect or interact, the system developer interacts with different users of the system. Interaction between system and elements is convergent and divergent and interactions must begin at a very early stage in system development.	Elements used to develop the system may be physical or cyber objects, as well as personal experience, knowledge bases, etc.	Elements used to develop the system include a wide diversity of constructs, from tangible hardware to personal experience and culture
Task of joining and assembly	Task of organizing, negotiating, and sharing information and resources	Task of converging aspects of different elements (concepts, knowledge bases, etc.) to arrive at an integrated solution	Task of co-creating a new capability or knowledge bases, etc. by drawing upon different knowledge bases (expertise, or capability, etc.) in order to conceive of a new system or to address a problem. The new system (or problem solution, etc.) is a homogeneous collective of a diversity of elements/inputs (the diversity of which was essential) where the collective system capability transcends the sum total of the original elements/inputs

Connecting	Coordinating	Collaborating	Collective
Attention directed to the interface where the elements connect, and toward the interactions at the interface	Attention directed to clarifying user preferences and negotiating a common ground between users.	Attention directed to interactions between elements in the integrated solution. The concept of "the interface" between elements loses significance as the integrated solution requires iteration and some modification of the elements	Attention directed toward incorporating, fusing, and embodying different wisdom, inspiration, tacit knowledge, assumptions, experience, etc.
System is a combination of different joined elements	System is dynamic and evolves as elements (user needs) change.	System is combination of different integrated elements. The original elements have been partially modified during the integration	System is a collective (or somewhat of a fusion) of diverse elements.
Individual elements are physically connected but distinct, with little (relative to element size) modification to facilitate connection	Elements of the system (user needs) are inherently dynamic and sometimes irrational. User needs (elements) may or may not be altered due to interaction with the system.	Individual elements are partially merged and/or physically integrated to create the overall system or solution, yet the individual elements remain somewhat distinct in the system	Individual elements (which may be physical concepts or personal knowledge and expertise) are fused together, becoming irreducibly intertwined to create a new system where the original individual elements may or may not be distinctly apparent in the created homogeneous system - hence, contributions of the individual elements to the system are not necessarily clearly separable after forming the collective.

Connecting	Coordinating	Collaborating	Collective
During R&D of the elements, infrequent interaction between element researchers and developers generally occurs and is likely not needed. Technology maturation of each element occurs primarily within a domain area. Significant interaction is required for connecting the elements after they reach a specified state of maturity. Interaction is mostly convergent.	Elements (users of the system) of the system may or may not interact. However, the system researchers and developers interact continuously with elements beginning early in R&D.	A greater level of tacit knowledge sharing is generally required compared to connecting, thus participants that 'own' the different elements of the system must interact in physical proximity for some portions of system development. Interaction between disciplines is very high once the elements reach a specified state of maturity. However, as the integration is a merger of different elements, requiring potentially significant changes to each element, interactions begin earlier in R&D than for a *Connected* System. Interactions between disciplines are mostly convergent with occasional divergent discussions.	Highly divergent and convergent interactions; Divergent as the team interacts to create aspects of a new system; Convergent as they determine how to develop the system. Emergence of a new system (or solution to a problem) with new capabilities, not previously envisioned, often occurs. Interactions require working together frequently with the highest levels of tacit knowledge sharing. Interactions between disciplines begin early in R&D. Single discipline R&D still continues but is influenced by the work of the collective.
More of a multidisciplinary effort	More of a multidisciplinary effort between the elements; however, the system developer's effort is highly interdisciplinary and, depending on individual creativity and opportunity, it may be transdisciplinary.	Collaboration begins with a multidisciplinary effort but ends with an interdisciplinary effort.	Inherently interdisciplinary with frequent trans-disciplinary results

Connecting

Connecting is more of a multidisciplinary effort to join separately developed elements and their respective individual disciplines. In this scenario, the researchers that develop the different elements work largely independent from one another until the last stages of their research. This effort is multidisciplinary in the sense that information between the different elements is exchanged yet individual disciplinary methods and theoretical concepts are not questioned or modified but rather updated with additional information such as operating conditions.[17] The elements of the system are largely modular. The researchers do not interact significantly during R&D and early design though they may provide R&D results and other information to a lead integrator separately with little detailed awareness of or knowledge integration with other disciplines. This enables the straightforward comparison of two elements for the same function in a system via "plug and play", where the pros and cons at a system level of one element versus another are compared by "plugging in" one element and evaluating the system's performance ("play"), then removing that element and "plugging in" the comparative element and evaluating the system again ("play").

Example systems that primarily consist of *connecting* elements are computer assembly; updating existing systems with new technologies; swapping out different technologies in a baseline system model to determine the change in the system's performance; and, more conceptually, a jigsaw puzzle or mosaic. One team leader with 25 years experience described a *connected* system as a *"patchwork quilt."* Another team leader with similar experience described a weak connection between disciplines as: *"I don't see there being any connection between—a lot of the disciplines don't have much connection between themselves, …the [A] group doesn't really have to work with the [B] and [C] group or the [D] group, except for maybe saying, 'Okay, here's the boundary conditions of the [end] of my [element] to go into the [their element].' They don't have to do much interaction."* As portrayed in this quote, the researchers in a *connected* system exchange information creating a multidisciplinary system but they do not conduct R&D interactively nor integrate their knowledge and adjust their understandings, methodologies, or theories in an interdisciplinary sense.

Connecting offers the least social and organizational effort since the elements needn't interact until near the very end of their development. Thus, what may be considered as "program management overhead costs" may be small. Perceived (but not necessarily actual) system development risk is lower since the elements are known and defined. Traditional stepwise program management processes are easier to implement, as the elements and the system are known or are well defined.

However, the lower cost and lower risk perception must be compared with a significantly decreased opportunity for creativity as compared with the other methods. The system design is constrained by what the individual elements develop separately. Because integration occurs after a lengthy period of the elements being developed separately, the developers of the elements have significant investment in their element both emotionally and professionally. Thus, individual participants (the element developers) may be less interested in opportunities that may emerge between the elements or in exploring significant modifications to their elements, particularly given an organizational culture that rewards single-discipline achievement. Many who worked in a *connected* manner described more turf battles and myopic thinking than resulted from the other methods of interacting.

Coordinating

Coordinated systems are unique from the other three systems described in this section, as the elements are users of the system as is the case with networked systems such as transportation systems or Wi-Fi systems or a power bus that is used by many elements. In these scenarios, the elements may or may not interact yet the developers and operators of the *coordinated* system must work interactively with the different elements to clarify user needs and changes. In many cases, the performance of a *coordinated* system may be improved if the users (elements) work together, however, this is not always an option. Hence, there is more of a multidisciplinary effort between the elements; however, the system developers' efforts are highly interdisciplinary and, depending on the creativity of the developers, their efforts may be trans-disciplinary.

Examples of systems primarily using efforts of *coordinating* are: hardware, software, testing platforms, etc., that are shared by many users; a laboratory or field

center where many similar or disparate researchers work; or, more conceptually, a family vacation. Some project or team leaders or line managers oversee their project, team or line in a coordinated sense by managing several different tasks that all share a common topic area and resources (computers, offices, office staff, funding source) but the tasks are being conducted largely independently. Some respondents described their jobs of providing summarized information of different research efforts in their group "up the management chain," in order to address upper level reporting requirements, yet they did not expect the researchers in their group to interact. One MDO researcher replied that: *"we do integrate from different disciplines into our model, but we do not require them to integrate."*

A *coordinated* system is more of an orchestration of elements and these elements may not actually work together in a relational sense but do so temporally as needed. Hence, a *coordinated* system does not require the elements of the system to interact, but does require the system developer to interact with the different elements very early in system development and to sustain interaction and communication with the elements (users) throughout development. In contrast to the other three methods, the *coordinated* cross-disciplinary elements may not necessarily be viewed as a distributed cognition system.[57] In *coordinating*, the elements are often users of the system rather than interactive contributors to system development. The social skills (such as negotiating and listening) of the system developer (which may be a network of developers) are paramount in *coordinating*, as the social needs begin early in system development and are sustained.

Further, the system in this scenario is really never "complete," but rather "current" and continuously being updated and morphed as users and user needs change. The development process is thus less stepwise and defined. Here, success of the system may not be the system's ability to address the current needs, but instead, success may be best measured as the system's adaptability to address changing needs, the latter being more challenging to quantitatively measure a priori and requiring larger upfront costs. For management, the constantly evolving, higher upfront costs for developing more adaptable systems, and unknowable future state of a *coordinated* system create challenges in some traditional processes focused on known system states.

Collaborating

The interactive merger of different concepts and ideas creates *collaborated* systems. Here teams work together to adjust partially developed elements to work cohesively together. The elements are much less modular and much more interdependent than in a *connected* system. An example *collaborated* system is a physically integrated system that contains two distinct but interwoven sub-systems such as a landing gear and a wing where the landing gear folds inside the wing. In this scenario, the R&D teams for the landing gear and the wing may work separately for a portion of the development period (multidisciplinary effort) but the sub-system interdependence requires interactive work practices (interdisciplinary effort) much earlier than for a *connected* system. Another example of a *collaborated* system is merging and changing the capabilities of two software packages to create a new integrated software package with enhanced capabilities. Conceptually, a collaborated system may be envisioned as a tapestry or a composite.

One researcher with 30 years experience, who typically functions in an integrating role, described his/her ideal for a *collaborated* system as: *"Having a common product, … that acts as a focusing lens. It brings people together because you know there's one group, the integration group, that's responsible for the whole thing. And they're pulling resources from all over the company in, and all the people in the company have a focus down to that product."* Another senior researcher in a single discipline area with 30 years experience describes his/her personal experience in a *collaboration* as:

> *"In [this cross-disciplinary team], we do some face-to-face meetings and we do some electronically because …there's [Daniel], the [Element A] guy, [Sarah] is another [Element specialist, Element B]. [Abraham] down at [our other site (several states away) working on Element C] and so forth. Even [Joseph] now from [another site several states away] is joining in. We have to collaborate on the phones. Things get iterated back and forth. I mean I have [Element D] that [addresses these parameters] and [Daniel] kind of takes that and adds [Element A] stuff, and [Abraham] then [adds Element C], and it all goes around and around and around, and finally converges to something. Every one of us needs something because none of those other guys knows anything about [my Element] that I haven't told them. I don't know anything about [their Elements], until these guys have told me."*

Collaborating presents greater social and organizational challenges than *connecting* and *coordinating* and is best understood as the work of an IPT. Logistically, as teams become larger and geographic dispersion grows, the organizational overhead of enabling *collaboration* can become significant. The system design is not as constrained by contributing elements as in the *connected* system; however, this also means that defining a detailed system design requires more time.

Collective

The work of a collective may be seen as a highly concentrated collaboration where interaction among researchers begins early in R&D and team members may co-locate for extended periods to facilitate the needed interactions. *Collective* interdisciplinary interactions involve different disciplines striving to achieve a common goal (a new system or innovation) not by focusing on integrating existing technologies, but by proactively exploiting and fusing diversity of thought that is resident in the team members. The resulting co-creation of knowledge further enhances the diversity of thought as team members re-think their incoming assumptions. *Collective* efforts are inherently interdisciplinary and often trans-disciplinary – the resulting need for significant face-to-face time makes *collective* action challenging for highly dispersed teams.

In a sense, collective R&D is designing while researching and developing. For example, *collective* effort can be interactively working with people of multiple backgrounds to create a new system that is not constrained by the need to incorporate existing elements previously created by the people on the team. Rather the knowledge and experience generated from single disciplinary research is what is integrated more so than existing hardware and software. Conceptually, *collective* action may be envisioned as creating a homogeneous alloy that gains from the various capabilities of different metals. A team leader who encourages collective action describes it as: *"The entire team is responsible for that solution. It's not the lead engineer signs off and it's his job. It's not that. It's the whole group owns the solution."*

Cross-disciplinary interactions that are *collective* in nature require the most interaction between disciplines. A diversity of literature addresses the theoretical basis

of collective constructs and inspired the use of the term here.[4, 49, 51, 80, 115] The literature on collective constructs includes, for example, examining collective efforts for aircraft carrier operations[4], knowledge management[57] and knowing in practice[49]. One exemplar from the literature in sensemaking theory will be examined to provide insights from theory on collective interactions across disciplines.

Weick's research on "collective mind" in sensemaking theory describes some of the aspects of "interrelating" that are essential for developing a system collectively. [4]·[80] The research on collective mind considers the cognitive processes of a group that must heedfully work together to achieve a solution, and hence, provides a useful organizational perspective concerning the collective nature of the interactions described above. The organizational perspective of collective mind focuses attention more on active processes (or *how things are being done*) over an outcome (or *what things are done*). For example, Weick portrays "collective mind in terms of method rather than content, structuring rather than structure, connecting rather than connections. Interrelations are not given but are constructed and reconstructed continually by individuals (Blumer, 1969: 110) through ongoing activities of contributing, representing, and subordinating."[4] This perspective suggests a focus on the processes of interacting as well as the products of these interactions in conducting collective R&D interactions.

It is also important to note that collective mind (in *collective* interdisciplinary teams) can occur in underdeveloped groups provided the interrelations between group members are done heedfully, meaning their interactions are more or less purposeful, attentive, "tied together by trust," mutual respect is valued over agreement, diversity of thought and experience are embraced while coordination of action is emphasized.[4] In collective mind teams focus on "interrelating their know-how" which improves comprehension of a system in three ways:

> "First, longer stretches of time can be connected, as when more know-how is brought forward from the past and is elaborated into new contributions and representations that extrapolate farther into the future. Second, comprehension can be improved if more activities are connected, such as when interrelations spanearlier and later stages of task sequences. And third, comprehension can be increased if more levels of experience are connected, as when newcomers who take nothing for granted interrelate more often with old-timers who think they have seen it all. Each of the three changes makes a pattern of interrelations more complex and better able to sense and regulate the complexity created by

unexpected events. A system that is tied together more densely across time, activities, and experience comprehends more of what is occurring because the scope of heedful action reaches into more places. When heed is spread across more activities and more connections, there should be more understanding and fewer errors. A collective mind that becomes more comprehensive, comprehends more."[4]

An experienced team leader from a single discipline group who is responsible for a highly cross-disciplinary team describes the benefits of gaining a more comprehensive system view by working *collectively*:

"*So, you got the 'gotta-haves' and the 'want-to-haves' and the 'it-would-be-nice-but'. Oftentimes, if you don't understand the system you don't understand the something that may be on that 'it-would-be-nice-but' can cause a revolutionary change if you can make one of those 'it-would-be-nice-buts' into a 'gotta-have'. … They didn't know that we could build things other ways. Nobody had asked them, 'Well, gee, what if you could build this some other way? How would you do it?' They said, 'Never been asked that.' So, then they started looking under these rocks and all of a sudden they're going: 'Oh my gosh! There's this whole field that we found that's never been plowed that has some rich possibilities, very great capabilities.' …[Meetings are] much more dynamic. There's a lot more interrelationships, a lot more talking back and forth and the different people in the room that are representing different disciplines are asking questions.*"

One challenge in managing a *collective* is that a clearly defined system design remains elusive for a much greater portion of the R&D effort as compared to other methods. However, these highly interactive exchanges between disciplines begin early in the R&D effort and continue throughout their development effort, offering the greatest opportunity for creativity and innovation in the system as well as the relevant single disciplines. Respondents described the *collective* as an on-going two-way feedback loop between discipline-focused research and system-focused research. However, the informality of this feedback loop, the significant tacit knowledge that is shared, the iteratively divergent-convergent nature of the collective, and the extended time required to specifically define the system design make quantitatively measuring progress in a collective extremely difficult by conventional stepwise program management processes. Hence, while the respondents who described *collective* action were strong supporters of its benefits, they acknowledged that it occurs infrequently and is not well understood by many in their organizations. Note, few respondents specifically referred to their efforts

as a *collective*; yet the descriptions of several respondents were consistent among the data and corresponded with literature on collective constructs noted earlier.

All of the conceptualizations above (connection, coordination, *collaboration*, and collective) may embody some aspects of collective mind; however, the inconsistency and less mindful nature of interrelations in connection and coordination efforts reduce the opportunities for collective action considerably, for collective mind is built on a well-developed mutually shared field of the heedful interrelating which is tightly coupled, but the tight coupling is social rather than technical.[4]

Collaborative and collective efforts share some similarities. For both, opportunities for new knowledge creation abound, aiding both single-discipline R&D and system design. As stated by Madhavan and Grover: "frequent interaction among team members can contribute to the building of strong ties between them (Krackhardt 1992), which further facilitates the use and creation of knowledge within the team."[57] Much of the knowledge is held tacitly or collectively, making interpersonal relations more important while simultaneously making information sharing more difficult. Both *collaborative* and *collective* efforts also become greatly strained as teams become larger and more dispersed. Correspondingly, respondents tended toward more *connected* or *coordinated* action as team size grew or as team members became more geographically dispersed.

Discussion on the 4C's of Combining Elements in a System

These four methods of interacting between disciplines were the primary methods that emerged from the data. As noted earlier, the significance of these different methods is that most respondents were not clear which method was expected of them and expressed some frustration as they described their efforts in trying to accomplish one method of interacting while others they were interacting with had different expectations. Further, upper management often evaluated the output of each of these four methods with the same lens though each method requires different levels of interaction, proximity of work, and clarity of system definition. The challenge with this last observation is multi-fold as the opportunities, outputs, costs, and needs of each

method are quite different. In this section, I will elaborate on some of the challenges in communication, terminology, and different system views.

Differences in the Final Engineered System and the Corresponding Integration Terminology Used

The system design that results from each of the four methods may be quite varied. The corresponding system integration terminology has great equivocality and related confusion in the organization. For example, the terms interface, interaction, interdependency, and decomposition are used extensively in describing the relationships between elements in an engineered system. The related engineered system-to-engineering practice connection stipulates much of the cross-disciplinary interactions in engineering practice that are the focus of this study. While the academic definitions of these and other system integration terms are clear to nearly all the respondents, the *variations in their implications to the engineered system and the organization* pointedly are not clear among most in the organization. The resulting variations in assumptions and perspectives have widespread impacts on engineering practice. To illuminate the variations in terminology, related system implications, and impacts on engineering practice, I focus discussion on two terms specific to the current study: the interfaces and interactions between elements in an engineered system and related cross-disciplinary practice.

Interfaces

Literally meaning "the common boundary between two bodies,"[18] the term *interface* is used to describe the place of connection between two or more elements in a system. Interfaces are most critical in a system integrated by *connection* as the system may be described as a combination of modular elements. Interface has less meaning in a system integrated by *collaboration* as the elements were designed to integrate more cohesively and distinct interfaces begin to blur. To an even greater extent, the term interface may have little meaning in a system integrated by a *collective*, as boundaries between elements can be abstruse. For example, while the keypad-headset boundary

is distinct on a traditional desk phone, this boundary is less clear on a touchpad-driven cell phone. The term interface has many meanings in a coordinated system as elements of the system may or may not interact yet they share a common system.

In practice, these variations place communication challenges in using an Interface Control Document (ICD), which is a routine and expected part of the system engineering process that follows R&D and early design. Processes such as completing an ICD may not be the most effective manner to describe the less modular nature of a collective system or the ambiguous nature of interfaces in a coordinated system such as a transportation system.

During R&D, engineers often look for clear interfaces between traditionally distinct disciplines to provide boundary conditions and initial performance conditions for their work between disciplines. Interface specifics have been used for decades as a way of communicating system integration details; as such they provide a common way for engineers and scientists to make sense of an integrated system. For highly modular systems, interfaces are appropriate. And, modularity is an essential element in the design of many systems.[29]

However, as noted, clear interfaces between some system elements (and hence disciplines) do not exist for some large engineered systems. Further, attempts to create clear interfaces to simplify practice may result in setting up the R&D work in a manner that does not lead to the integrated system performance desired (e.g., the touchpad-driven cell phone). More discussion about the structure of research practice and its implications will be presented subsequently.

Interactions

As interactions between elements increase, interfaces blur. The term *interaction* is used to describe the "mutual or reciprocal action or influence"[18] between elements. While interactions between elements are crucial for all integrated systems, the timing of when cross-disciplinary interactions occur varies with the four methods of combining disciplines. In a *connected* system, interactions are examined primarily near the end of the R&D efforts for each element. Thus, engineers and scientists working on the different elements may largely work independently for most of the research effort.

Similarly, elements need not interact in a *coordinated* system, though interaction may be helpful. Thus, in practice R&D engineers and scientists work more sporadically together in developing a *connected* and *coordinated* system.

For example, a respondent describes his or her work in sharing (or *coordinating*) information: *"We'll have periodic meetings where we all share information, but the work is not largely collaborative. It's making sure we understand what information the other one needs, going back and doing our own work, and then meeting up periodically to make sure that we have the interchange that's necessary so that everyone get their work completed."*

In several cases, respondents described the traditional ways of working as: *"just tossing stuff back and forth. To really get them to integrate is very, very hard. Because they're each focused on their own need to get [their element] developed. And, they've been the requirements [for their element]."* Like many others, a respondent, who is a team leader, describes the team efforts as mostly coordinated and connected activities with some interaction (and hence collaboration) near the end of each element's development effort (a few words related to timing and consistency of interactions between team members have been underlined for emphasis):

> *"I think there's parts where it's somewhat collaborative. They might get together and sort of talk about what our objectives and goals are, and what needs to be done to get there, and then we might independently go and address [individual] issues. Then keeping people informed who are part of the team to make sure we don't lose sight of [system-level trade-offs]. … And then [later] as you start coming to a point where you actually want to put these pieces together, and show that I have a viable concept, then you need to start saying, "Where am I going to put this, and how am I going to bring it together to make it work?" Then you've got to be sure that although we've talked about [discipline A – discipline B] interactions, [and discipline C], now we're actually starting to come home to actually put it together. Now you've got to start to think about real application. Functionally, I've got [individual elements] that should work. Now I've got to start bringing these together because I'm actually going to do a demonstration test on some relevant environment. …Then you have to start bringing all [system realities] to bear."*

Conversely, for a system developed via *collaboration* or a *collective*, interaction between elements is a defining system characteristic and begins earlier in research. As the elements are inherently developed in a more intertwined manner, the properties of some elements may change due to interactions with other elements. For example,

describing the start of a collaborative effort, a line manager with 25 years experience replies: *"Group A you're working on this, group B you're working on this. We're starting to see from the system studies and everything else, it seems like we could actually get the [system performance] that we're looking for if we kind of integrate the technologies that you all are bringing your respective technologies to the table together, and look at something, an integrated approach rather than just two separate approaches."*

And, systems developed by *collective* action may be partially or wholly defined by element interactions from their inception, requiring cross-disciplinary interactions beginning early in R&D. A team leader with 30 years experience notes: *"That [system problem] is a huge nut to crack. That isn't a [discipline A] problem. It isn't just a [discipline B] problem. It isn't just a [discipline C] problem. It's multi-disciplinary in nature, so you have people from different elements that need to come together to find out what are the unknowns that we need to attack to make this work."*

In all cases where respondents talked about *collaborative* and *collective* approaches, they consistently noted that the engineered system's performance depended on an integrated approach in R&D where team members must work interactively together. Particularly for *collective* efforts, respondents who were team leaders guided their teams with strong desires for integrating early: *"from day one, you come to the drawing board."*

Differing Views on Cross-Disciplinary Interaction Needs

Disagreements regarding interfaces, interactions and interdependencies among disciplines, or how best to use them, was an oft-noted lament during the interviews. An example from one respondent:

> *"The [discipline A] folks basically said just give us [this interface]. We don't care what you [do in your discipline]. We don't care how much [you do this]. Just make it so it [meets the interface requirements we have]. So, based on that interchange, my general feeling was they felt like they didn't need us. They were dictating the [the interface] and as long as I [did that] they didn't care about what I did in my discipline. [The systems] are very interconnected and no piece works in isolation from the other piece. So, they are all interconnected and they're all trading off. So the reality is that …I can [meet their interface demands perfectly], no kidding, … but you're never going to get it [the overall system to work]. And., that's not going to suit their needs. So, the tradeoffs that I have to make in*

[disciplines B and C] are going to influence [discipline A]. So, if I [just meet their interface condition] we're going to have a non-optimum [system] solution."

This vignette (that captures many sentiments from other respondents) shows that a disregard for the significance of another discipline can create rifts organizationally and dishearten some from purposing future work with another discipline that does not respect the impact of their work. Lack of mutual regard for the technical contributions of another discipline often elevated a technical disagreement to a social disengagement between organizational units. When these disagreements persisted, negative emotions of frustration and anger often followed.

In an opposite scenario, the following respondent spoke with a sense of validation when another discipline realized that a previously held boundary between them was preventing the other discipline from reaching a challenging engineering goal:

The [discipline A] guys realized that they cannot build [high performing discipline A sub-systems] to meet the challenging goals without running into [a problem our discipline can fix]. They run into [this problem]; in order to have the [their sub-system] perform, you have to have some kind of [work from our discipline]. One [discipline A] guy within the [discipline A line organization] realized that [our discipline B] was important, and then he worked with our [discipline B] guys to say, hey, they feel like you're an important part of [the discipline A sub-system] development. There's a mutual understanding that they need us, and then we can help them. They provide us the knowledge of [their sub-system]. The [discipline A] guy and [our discipline B] guys are co-lead. We don't know much about [discipline A] stuff, so he provides us knowledge about [discipline A]. We do the [discipline B], but then we work together. That's how we do one and one and make it more than two, us working together. It's not like, here is a [discipline A] model; go do the [discipline B] work. We're working together. We're defining the requirements together. He's working with us on developing [a combined test], so it's a collaborative effort. Everybody is seen as a so-called equal partner. Every contribution is valued."

The above two examples, which represent the comments of many respondents, highlight some of the significant social aspects regarding connections between disciplines. The degree to which disciplines interacted and the quality of their interactions often heavily corresponded to the respect between the groups and the value one discipline placed on the other. The importance of mutuality and reciprocity in working across disciplines was a common theme in this study. This finding ties well

with research on building positive social capital in organizations where mutual regard, respect, and reciprocity are a few of the principal tenets.[67]

Two Paradigms In Understanding System Behavior

In taking a comprehensive examination of all of the data, two predominate paradigms regarding understanding system behavior emerged. The 4C's provide a means to depict these two overlapping paradigms. Regardless of the method of combining disciplines used and, often, regardless of the behavior of the final system, respondents' perspectives on how the disciplines or elements in a system come together tended toward two chief paradigms of system behavior that I summarize in Figure 6.

One paradigm concentrates on understanding the system as the deterministic result of connections and coordinations of mostly modular elements that may be organized with sufficient accuracy in a hierarchical decomposition of the system, yielding system behavior with significant uncertainty but sufficient predictability.

One prevailing paradigm or perspective concentrates on understanding the system as the nondeterministic result of a collaboration and a collective with many irreducibly intertwined elements that are often intricately networked such that decomposition inherently omits some aspects of system behavior, yielding ambiguous system response that may be explainable but not fully predictable.

Figure 6 Two Paradigms in Understanding System Behavior (Source: the Author)

The former perspective may be summarized as a "more modular view" of the system and the latter perspective as a "more complex view" of the system. It is important to note that these perspectives accurately represent the characteristics of many systems, as some systems are more modular and some are more complex and many systems are a combination of both. The finding here is not to distinguish different genres of engineered systems but rather to distinguish the underlying, typically

unwavering, paradigms held by the respondents that served as a basis for how they made sense of systems. The dichotomy in perspectives often determined the cross-disciplinary approach that was taken by the respondents. Respondents with a more modular view preferred *connections* and *coordinations* of disciplines, while respondents with a more complex view preferred *collaborations* or working in a *collective* manner.

Several respondents complained that some members of their team or greater organization had a contrasting mental model of engineered systems and how cross-disciplinary interactions should take place, straining their working efforts. The different paradigms are often related to what respondents considered was a part of the "system." For example, a transportation system may be described as a *coordinated* system of different vehicles in a largely modularly networked system. Or, the same transportation system may be viewed as the *collaboration* of many different local municipalities whose influence on the system and the vehicular traffic cannot be ignored.

The more modular view has been the foundation of engineering education and practice for many decades. As noted earlier, in recent years, considerable attention has been given to a more complex view of some engineered systems. The latter view has strong ties to systems theory and complexity science.[30, 41, 42, 45] This view is also far less prevalent among respondents as nearly all respondents were trained in a more modular view of engineering. Hence, all respondents thoroughly comprehended the more modular view; however, many did not clearly comprehend the more complex view. Not surprisingly, respondents with the more complex view of systems felt misunderstood by many in their organizations and expressed frustrations when their system perspective varied from those with whom they worked. Both perspectives value single-disciplinary and cross-disciplinary R&D. The key differences are in how, when, and the extent to which they work across disciplines. For example, a line manager with a more complex view describes integration as something accomplished during not after single discipline R&D: *"So, being able to see those interrelations between the disciplines and how they are not just insolation … that's where you get your revolutionary changes in technology is when you integrate research from different disciplines."* In contrast, a senior researcher with responsibilities for integration acknowledges that while he/she is focused toward integration, his/her group still

struggles with a more modular view in the overall organization: *"We've become so kind of myopic. We're looking at our own things, and those have become so complex that we forget to look at each other and for ways to collaborate there. It's almost like you don't see the forest for the trees."*

In the more modular view, respondents prefer a more building block, reductionist approach to R&D and early design. They understand the system as more of a combination of separately developed elements and disciplines that are modularly networked. Integration and interaction with other disciplines are preferred later in R&D after details of individual elements are well understood. Those with a more modular view prefer to further decompose the system until components can be fully understood. Multifunctional elements are cognitively understood by breaking down the functions or pieces into a *connection* of different pieces or functions.

In the more complex view of the system, the system is viewed more widely to include existing known elements as well as elements outside the scope of the current organization. Interactions are privileged over elements as interactions are seen to impact the element properties. Hence, the system properties are best defined as the *collective* response of element interactions and decomposition inherently loses some system behavior. Similar to system and complexity theorists, those with a more complex view assume the system is "too big to know" comprehensively and emergence is inevitable. Though modularity may be desired for some elements of the system, actual interfaces between elements are assumed to be ambiguous and dynamic. Multifunctional elements are cognitively understood as a *collective*.

Some respondents noted that they see a gradual change from a predominance of the modular view to more considering the complex view. A researcher with 8 years experience replies: *"We've worked the individual components for a long time, but I think there's more and more recognition that understanding the interactions, that optimizing in isolation doesn't get you to the best answer for the system and that we're going to have to work together and understand how we can trade, not just within our disciplines, our component, but through the whole vehicle."* Some respondents considered the more complex view as systems thinking and the more modular view as lacking a systems view. However, the data obtained does not support this perspective consistently. Both

paradigms "see" a system, yet with different perspectives, both of which are applicable to different classes of problems. The chief effort of this work is to note that these two paradigms create a tension in the organization and result in misunderstandings and work preferences.

A Single-Discipline as a System in Cross-Disciplinary Interactions

The 4C's of Combining Disciplines also describe another finding in this study regarding cross-disciplinary practice, where a single discipline becomes the system of interest (a micro-system) and the focal point for integrating disciplines. This common practice may be referred to as technology integration and advancement, or more colloquially as technology push. It involves a largely single-discipline team methodically advancing or maturing a technology that was researched and developed primarily within their single discipline area. The technology is advanced or matured by drawing upon a diverse set of other disciplines to support the single-discipline team in analyzing and testing their technology. Maturation of the technology focuses on adding more degrees of freedom or increasing model fidelity or application realism from a single discipline perspective, such as advancing from a two-dimensional model to a three-dimensional model or advancing from the assumption of linear forcing functions to non-linear forcing functions. In the latter, data for the non-linear forcing functions may derive from another discipline. As described further below, this approach where a single-discipline is a micro-system creates a very different interactive scenario than when a diverse set of disciplines interacts to enable a macro system that is beyond any one discipline.

Though this practice is focused in a single-discipline area, data from other disciplines may be obtained without significant interaction with the other disciplines by proceeding via *coordination* or *connection*. In a *coordination* among disciplines, the single-discipline researcher or team obtains data from the other disciplines regarding boundary conditions (e.g., dimensional data), operating scenarios (e.g., voltage, temperature), etc. This external data increases the realism of the single-discipline R&D while protecting the control volume that has been drawn around the single-discipline technology. Protection of an effective "technology control volume" is often the focus of

this effort, where the technology is matured without adding or increasing potential interdependencies from other disciplines. This enables a detailed understanding and analysis of the technology largely within a single-discipline area while keeping everything else in the macro system the same.

Alternatively, significant interaction with other disciplines can occur via a single-discipline focused *collaboration*. In this type of *collaboration*, all other disciplines are interactively aiding the single-discipline research team in advancing a single-discipline technology. This is a common practice in laboratories where extensive testing is conducted and researchers from many disciplines *collaborate* with the single-discipline research team to ensure the technology is evaluated accurately and thoroughly. This type of *collaboration* enables highly sophisticated controlled experiments and rigorous technology evaluation in a single-discipline area.

Single-Discipline as a Micro-System – Potential Impact on Macro-System Design

The practice of a single-discipline as an integrative focus facilitates a building block approach to R&D where new data (a new "block") is added only after previous steps (blocks) are well understood. This approach greatly diminishes ambiguity that often results from interdependencies with other disciplines, making one of the principal challenges uncertainty. Cognitively, this approach enables depth of technology understanding that can be extremely beneficial for future macro system *collaboration* or *collective* exploration, where the understanding of the technology (more so than the technology itself) is what is utilized in the macro system *collaboration* or *collective*. This practice answers the questions of "how does this technology work?" and "how will the macro system be improved by using this technology if everything else in the system remains the same (including previously identified interdependencies)?"

Viewing this practice as a precursor to macro-system design draws attention to the underlying methodological assumption that the technology is not highly interdependent with other elements in the macro system. While technological evaluation in this manner is less ambiguous it can also be less accurate for some macro system applications, as potential interdependencies with other disciplines or macro

system elements may be overlooked. For large-scale engineered systems, some technologies are added to the system in a modular fashion in a *connection* where the assumption of minimal interdependencies is valid.

However, the benefits of many other technologies can only be realized when the interdependencies with other macro system elements are considered during technology maturation, not near its culmination. In a sense, some benefits of single-discipline technologies are realized only when disciplinary interdependencies are exploited rather than controlled. This particularly is the case when the technology will not be merely retrofitted to an existing system, as may have been the assumption during single-discipline technology maturation.

Frequently, several respondents proceeded toward conceptual design of a macro system by aggregating the outputs from several single discipline (as micro-system) efforts, where each micro-system may have assumed varying control volumes and thus interdependencies with their respective technology. This approach to conceptual macro-system design favors the more modular view of systems, where the micro-system inputs are rigorously *connected* into a macro system design using well-validated data from individual elements. Those with a more complex view of systems regard aggregating varying assumptions and methods of cross-disciplinary interaction in a conceptual macro-system design as inaccurate. Additional discussion regarding integrating disciplines to enable macro system concepts will be presented in the next chapter.

Social and Organizational Aspects of a Single-Discipline Focus During Integration

Socially and organizationally the diverse set of disciplines interacts in a supportive role to the single discipline, where the interactions may be characterized as brief transactions of expertise that the micro-system (single discipline) must financially support. In the next excerpt, a team leader of a single-discipline focused effort describes some of the challenges in leading such a team.

> *"Then you have… to teach them what it is you need and make sure that they can do what you need. Then [one of the groups will say]: 'I'll need to have this data if*

you want me to [do my part].' So you go to [another group of] people and you have them get that data. Luckily [my discipline] has been an area of high interest. ... You have to then learn the language of everybody and be able to express your problem in a way they can understand. Then explain to the people with the money why you're handing it down three layers down to some other organization—why they're really critical to the whole process."

The quality of the relationships in the interaction varies greatly. When positive, long-term social connections can form creating a network of colleagues across a large organization that may build positive social capital.[55] Though one discipline is the focus of attention and leads the effort, this lead discipline sometimes attends to the needs of the supporting disciplines through seeking "mutual exchange, aid and benefit" among the team members.[67, 68] Another team leader of a different single-discipline team describes trying to understand the needs of the various teams members:

"It was just a whole lot of different parties. Everybody has their own area of expertise and their own 'why am I doing this?' (chuckle) It took us a while to get down to really understanding. And sometimes it was a matter in some groups, they didn't—they weren't critical. Well, like the [discipline A] people, what they wanted out of it was mostly just a little bit of support for some [support people in their group] so that they could finish paying for them for the year."

In some examples, the single-discipline focused effort expands to include the research needs of one or more of the supporting disciplines. In the next excerpt, a member of a single-discipline focused effort explains how his/her team expanded the team's research to include additional research in a supporting area.

"Well, we explain the problem. We show them [a needed piece of equipment] we had been using. [The supporting discipline with expertise in the piece of equipment] will probably tell us why they're failing, and then they'll make recommendations. ... They had to retrofit something on. [The needed pieces of equipment] are working better, but they're still not there, so we actually have a proposal for some ... funding to investigate—as part of a bigger project—to investigate improved [pieces of equipment] for [future experimentation]. We'll be using our own [in-house] group [with expertise in that piece of equipment]."

In these more reciprocal relationships, the team effort often transcends the original focus in the single discipline to a number of highly integrated research tasks across different disciplines.

Respondents also noted that when the quality of the relationships between the primary single discipline and supporting disciplines is professional but less reciprocal,

interactions can degrade to an approach centered upon simply meeting the stated requirements of the single discipline with brevity. A team leader of another single-discipline focused effort provides an example:

> *"Any good cross-disciplinary work I've done I've found that the other person has to develop some interest in your problem. Otherwise they're just a turn-key to deliver a product and then you're never going to quite engage enough to where they really can deliver fully what you need. They'll just do the minimum. Whatever you wrote down in your requirements document, 'here it is goodbye.'"*

This was a frequent lament of many respondents regarding working with the Multidisciplinary Design Optimization (MDO) or Multidisciplinary Design Analysis and Optimization (MDAO) groups in their organization.

MDO as the Focal Point of Interaction

MDO/MDAO groups have the stated purpose of integrating input from multiple disciplines in their organizations to evaluate or design macro-system concepts. However, many respondents viewed their interactions with the MDO group as working in a supporting role to MDO rather than in *collaboration* with the MDO group to further the evaluation or design of a macro-system concept of interest. Thus, most respondents saw the MDO group as a type of chief *connector* or *coordinator* to whom they supplied input. Few respondents viewed the MDO group as fellow *collaborators* and only a very small number of respondents indicated that they worked with the MDO group in a *collective* manner.

It is possible that the degree of reciprocity in the relationship between MDO and the supporting disciplines is a key factor. While all respondents highly valued the macro-system level, integrative work the MDO groups accomplished, respondents who worked with the MDO groups in a more reciprocal relationship were significantly more positive about their interactions with MDO. In these scenarios, the MDO researchers proactively sought more *collaborative* and *collective* interactions because they *"think that kind of flow of information and ideas is important."* Another MDO researcher described, *"You sit down at the table and you're sort of figuring out what's this person requiring of me or needing of me? Can I help them? Can I elicit from them what I need? Vice versa, can I give them something in return, sort of an- almost trading?"*

Respondents who noted little reciprocal benefit to working with the MDO group described their interactions more like paying a needed organizational tax than working in a mutually beneficial team arrangement. They described their supportive role to MDO as closer to a transaction of information. In recounting their time on an MDO-lead team, a single-discipline researcher with 20 years experience states that they *"never got anything out of it."* Correspondingly, some MDAO researchers described their interactions with other disciplines as largely a one-way interaction. An MDO researcher with 30 years experience describes the following:

> *"Mainly we need input from all the different disciplines. We probably can give back a little bit of information, but it's mostly them feeding us, I guess. … The MDAO [group] is really the [group] that has to do all the connecting. We are the cross-disciplinary, multidisciplinary group, so we have to do that connection. I think it's mostly a one-directional type thing. Which maybe is part of the problem as far as why they don't like working with—sometimes don't jump at working with us is because they have to give information to us and we're not providing much back to them, and so they feel like it's more of a chore for them … when we're not giving them information back."*

Another MDO researcher noted that when their group is working on a conceptual design of a macro-system, many of the supporting disciplines do not always feel like they are part of the macro system conceptual design team, although the macro-system concept is dependent upon the input of the supporting disciplines.

For all scenarios where a single-discipline or group (such as MDO) was the focal point of the cross-disciplinary interaction, the social relationship between the lead discipline or group and the supporting disciplines was paramount. In contrast to a scenario where all disciplines are working together to create a macro-system, having a single discipline or group as the focus of integration creates an implicit social or organizational hierarchy among disciplines that, in reality, are equivalent peers. The degree of mutuality or reciprocity in the interactions was a consistent factor in the ultimate quality of the cross-discipline efforts. Subsequent analysis in this work will turn focus toward interactions where disciplines are interacting to enable a macro system.

Chapter 6: The Influence of Organizational Structure and Engineered System Structure

Summary

This chapter addresses key impacts of the formal structure of the organization and the structure or physical configuration of the engineered system on the interactions between engineers and scientists of different disciplines. The central message of this finding is that structure can serve as both an initial condition and a constraint to the R&D and early design work, creating influential boundaries of action and thought, that may not apparent to many respondents and were likely unintended consequences of the strongly hierarchical organizational systems of many R&D organizations.

For the large-scale engineered systems that are the focal point of this study, R&D and early design teams are inherently large (hundreds or more) and the technological work extensively diverse, rendering a dispersed division of labor obligatory. In this chapter two related allegorical conceptualizations are created to illuminate the findings. One conceptualization simply titled the "Lamp Allegory" depicts some of the impacts of the structure the organization, project or program. The second conceptualization, titled the "Suite of Similar," describes the impacts of the structure of the product or system of interest. In both cases, it is clear from the data that structure is often assumed and usually overlooked as an influential aspect of the work outcome.

The structure of the organization and the engineered system frames the sensemaking (cognitive connections) and social connections of the engineers and scientists. Hence, changes to structure generate both confusing cognitive and social challenges while generating new creative cognitive opportunities. In the dearth of experience between established structural frameworks ignorance is inherent, making existing means of cognition incomplete and often inaccurate as heuristics and experience fail. Correspondingly, existing organizational processes can become more

hindrance than help. And, established hierarchical organizational and social connections become less effective.

However, the undefined cognitive, organizational, and social arena between established structural frameworks also provides a rich opportunity for the co-creation of new knowledge and competencies that are the hallmark of interdisciplinary and trans-disciplinary interactions. Respondents spoke widely of being engaged in transformative learning experiences where each discipline simultaneously learned different aspects about the same system — ultimately interactively co-creating new constructs that were impossible to create from a mere juxtaposition of disciplines.

The complex cognitive and organizational needs of these interactions oblige proactive attention to social issues, where deficiencies in social capital can have significant negative impacts. Respondents consistently emphasized a heavy reliance upon effective social capabilities in the organization to enable interactions between established structural frameworks and traditional disciplines.

Background and Introduction

The research questions of this study ask: What are the practices and perspectives on interdisciplinary interactions in R&D and early design of large engineered systems and why do these prevail and persist? This chapter addresses several aspects of the latter: why certain practices and perspectives prevail and persist. Based on the data, I focus attention on organization structure, engineered system structure, and associated cognitive and social characteristics. A brief review of the analysis thus far helps frame the current discussion.

Previously I discussed results of the survey, which heavily focused on the importance of social and organizational aspects in working across disciplines. The survey also showed that respondents believe the key advantages of cross-disciplinary efforts are cognitive benefits and system benefits. Given these results, attention in subsequent research was directed toward understanding the social, organizational, and cognitive aspects of working across disciplines and how these might impact the engineered system. Thus far, underlying organization culture was examined as well as

common cross-disciplinary practices and perspectives. For these analyses, the structure or arrangement of the people and engineering work was a fundamental feature that shaped much of the respondents' remarks.

In this chapter, I continue to explore the topics of social, organizational, and cognitive aspects with attention toward the underlying structure of the work. In describing their work, respondents consistently and explicitly noted organizational structure as a key influential factor. Respondents also consistently yet implicitly described various engineering frameworks within which or upon which they worked, such as hardware or software models, and the allocation of engineering goals and requirements, both of which were ordered and arranged by the physical layout or decomposition of the engineered system. Hence, the organizational structure of the engineered system also shaped or ordered many of the practices of the respondents.

While structure is the underlying topic, social and cognitive aspects are integral to this discussion; thus a number of social and cognitive findings are presented in this chapter as well. For example, words related to cognition appeared with very high frequency in the interview responses. The most common action words were words related to "thinking" and "knowing." Also, as noted previously, the focus of this study is interdisciplinarity; however, interdiscipline practices and perspectives are intermingled with all cross-disciplinary efforts and thus discussion includes multidisciplinary and trans-disciplinary efforts as warranted by the data.

Introductory Description of Common Organizational Structures

I begin this discussion with the recognition that all large organizations and all large-scale complex engineered systems must be decomposed into smaller portions for the sake of manageability. As noted by a senior aerospace engineering faculty, *"it is not if we cut up the system, but do we understand what the implications are when we do so?"* R&D and early design teams for large engineered systems often number in the hundreds and more typically the thousands. And, the content of engineering and science work for this early stage of system development is extensively diverse, including scores of specialty areas and a wide variety of different facilities, rendering a

distributed division of labor obligatory.

A common organizational structure used in many institutions, including the one studied, is a bureaucracy that is hierarchical in form, organized by expertise. Expertise may be structured by traditional academic disciplines such as tribology or fluid mechanics, or by system component or function such as propulsion or brakes. For the spectrum of engineering work studied (research through early conceptual design), typically the organization is structured around common academic disciplines while some of the engineering programs are structured by system component.

Respondents frequently referred to the different groups of expertise in the organization as being in "line organizations" and more colloquially as "silos" or "stovepipes." As described by one team leader in a line organization with 27 years experience: *"[Discipline A] people reside in a [line], and the [Discipline B] people reside in a [line]. The line organization is very discipline focused. The [line] management is the lead of that discipline. They go so far as to say they're the steward of that discipline and have to look out for that discipline."* As noted previously in the chapter on organization culture, members of each line organization are incentivized to become experts in a particular area, with line managers focused toward fostering high competence within the line's technical area. Line organizations can have approximately 15-50 people including contractors most of whom are co-located; however, laboratory or facility needs disperse some employees to nearby buildings.

A matrix organizational structure is also used with projects or programs created to manage the development of engineering products or systems. Programs or projects (hereafter simply called programs) can fund a wide spectrum of R&D and early design work focused toward specific engineering and scientific goals related to understanding scientific phenomena or enabling system performance metrics such as greater efficiencies or greater performance. This work may include small and large-scale efforts of basic research, analysis, testing, modeling, etc. The programs include R&D and early design work from several different line organizations (areas of expertise) located in different geographic sites often spread widely across the country. While programs are most typically known for drawing upon different line organizations to create and/or

develop a new capability, technology, or system, some basic research are organized by broad discipline areas.

A single program can fund 50 to several hundred people at several different sites plus many universities and contractors. Size and composition of the sub-groups within a program varies. One respondent from within a line organization described the content of his geographically dispersed program team as containing: a major contractor, a sub-contractor, two universities, two external research laboratories, and two line organizations within his home organization. This type of multifarious and distributed program team composition was common among most respondents.

As noted by other articles, geographic distribution of engineering teams for large systems continues to increase to address global demands and to obtain needed talent and physical laboratory capabilities.[23, 28] In developing and designing smaller engineering artifacts such as household products, the impacts of organization and system structure are often mitigated when entire research and design teams are able to convene, rendering their work more proximate in time and space. For the domain of this study, large organization size and distributed work are a defining characteristic. Accordingly, cross-disciplinary practices span not only different line organizations but also different buildings, geographic locations, and programs. The analyses herein do not directly address the physical challenges of geographic dispersion but rather focus on the social, organizational, cognitive, and system implications of it.

Structurally, geographic dispersion and organizational decomposition create inherent boundaries in the work. As noted by Repko, we are all surrounded by boundaries and "are mostly unaware of their existence until we find one blocking our progress."[6]

Regardless of the approach used toward organizational decomposition, each "cut" in decomposition creates boundaries, such as borders between requirements, mathematical models, assumptions, knowledge domains, incentives, working groups, and other factors. Boundaries are extremely prevalent and their influence persists far beyond the confines of engineering disciplines to include social factors (who talks to whom) and cognitive factors (how the respondents organize their thoughts).

The findings described subsequently emerged from innumerable comments from respondents who noted impediments in their efforts to work across disciplines that stem from explicit or implied boundaries in the organization. Respondents spoke less explicitly about boundaries generated by the structure of the engineered system; however, their comments were consistently framed by the decomposition of the engineered system. These decompositions in organization or engineered system usually become frameworks for systems engineering and MDO processes as well as other, more tacit, organizational facets such as culture.

Thus, this chapter focuses on two primary aspects of structure and related boundaries: the structure of the organization and the engineered system and the associated boundaries of action and thought that are influenced by those structures. The cognitive impacts of the structure and associated boundaries are significant and will be discussed throughout the findings. I begin with an examination of organization structure and follow with an examination of engineered system structure. I conclude this chapter with a summary of the social and cognitive implications of both structures.

Two allegorical conceptualizations are employed to more clearly illustrate the interdependency of work outcome and the structures of the organization, program, and engineered system in development. The approach of using fictionalized conceptualizations is known as "semi-fictionalized ethnography," as the conceptualization is firmly grounded in empirical data but fictionalized to convey findings.[100] This approach enables a thorough discussion of the findings while wholly protecting the anonymity of the respondents and avoiding inherent sensitivities related to any one real example. The first allegory, titled the Lamp Allegory, addresses organization structure. The second allegory, titled the Suite of Similar Architectures, addresses engineered system structure.

Impact of Organizational Structure on Cross-Disciplinary Practices

A large and varied body of literature describes an array of challenges and opportunities in crossing boundaries in organizations. One exemplar is Klein's work on crossing boundaries where she notes that long-standing communities may have

stronger implicit boundaries than others. For example, "tightly knit, convergent communities" "presumably have clear boundaries, circumscribed domains, and 'neat' problems that are controlled through cognitive restriction and social consensus." As explained in this excerpt, boundaries are formed and adjusted both cognitively and socially. The findings in the current study support this showing that the organizational structure serves an initial condition and boundary condition of the scientific and engineering work, creating boundaries of action (social) and thought (cognition) – all of which can significantly impact the engineered system development and ultimate design. In this discussion, I will describe common practices used to connect and bridge across large, spread-out organizations.

In the survey, organization structure, processes, and incentives ranked as principal enablers for interdisciplinary interactions. Pointedly, negative correlations of these topics were also mentioned as principal obstacles. Suggested organization structures that were enablers included "integrative teams" such as IPTs and structures that were not "stove piped" or "discipline-based." Suggested obstacles related to organization structure also centered on restrictions resulting from the common functional or discipline-based structures of R&D organizations and rigidity or inflexibility in the organization's processes.

Ethnography shows that historically, connections between elements of a large complex engineered system are data driven using extensive documentation, MDO methods, and design methods such as quality function deployment.[116] In systems engineering, Interface Control Documents (ICDs) are used extensively.[117] These methods of communicating what lies between elements in a system can rigorously deliver substantial information regarding what is known or identified through analysis. However, they can be a less effective means of discovering what is ambiguous or tacit – addressing these characteristics requires greater person-to-person interaction. [12, 46, 49, 56, 58, 59, 80, 118]

Outside of the processes dominant to MDO and systems engineering, cross-department connections are also made through a hierarchical construct of research and design reviews and other forums where diverse teams are encouraged to assemble. Several survey and interview respondents noted that opportunities such as these cross-

discipline events (as well as workshops) assist in encouraging cross-disciplinarity in R&D and early design by providing an excellent opportunity to increase awareness and identify research being conducted in other areas of the organization. Many respondents also noted that increasing knowledge of other disciplines also improves their single discipline research: *"Cross-disciplinary doesn't mean you're against core-discipline. In our examples, it always strengthens [core-disciplines]."* Table 12 lists other responses regarding enhancing single discipline research by becoming more informed of research in other disciplines.

Table 12 Enhancing Single Discipline Research By Becoming More Aware of Research in Other Disciplines

<u>Younger researcher with 8 years experience:</u> *"Even if I don't capture all of [what was said], I was able to take away pieces that, 'oh, I really understand why they did that. That makes sense.' I can take that and use it in my own research."*
<u>Senior researchers with over 20 years experience:</u> - *"Then I think in some respects having the bigger picture has enriched that deep dive [single discipline] information because now I start to see, oh, I never thought about [this area], or [this area in my discipline]."* - *"It's learning the whole business top to bottom and who knows where it may intersect with some other good idea and that will be a possibility for an idea. It's the stuff that you stockpile in your head that from time to time certain things start coming together and a new idea pops out. And maybe the parts that I generally don't directly worry about in my research but impact the actual application on a real [system] and real operations of a [system] and all that. That's what I learned more about. Which may come back around and I suddenly have some idea in the future I have. … I couldn't tell you right now today how that's going to improve something. I've haven't' got an idea for an experiment or a paper or anything else for it. I can store that back and I learn a lot that I think someday probably will come around wind up being part of a solution."*

While some formally organized events described by respondents offered an interactive setting with two-way discussions, most of the cross-disciplinary forums described tended toward presentations that fostered informative yet largely one-way communication. Socially, the lecture-style, one-way communicative forums enable emotionally safe and relatively easy forums in which respondents can gather knowledge without the negative emotional arousal of discomfort and embarrassment. Respondents often noted the uncomfortable social arena of working across disciplines with people with whom they were unfamiliar. More commonly, respondents noted significant challenges with being embarrassed by their ignorance of the other disciplines. While

knowledge of other disciplines is not explicitly expected, a culture that deeply values high technical competence implicitly values extensive knowledge as well.

Respondents often correlated being outside of their discipline with being outside of their "comfort zone." An experienced researcher notes: *"People don't want to feel like they're, you know, not competent. So I think there's a little fear that, if you step outside your comfort zone, it's an area you're not as sharp in, and you're not going to be the expert anymore. So it's uncomfortable to people."* The data suggests strong connections between discomfort and ignorance, even when ignorance was expected: *"Technical experts don't like to appear that they're not an expert in something, even if it's outside of their area."* Several respondents also used the word "stupid" to discuss ignorance, when lack of awareness or understanding of a topic is what they described rather than lack of intelligence, such as this researcher who regularly works in cross-disciplinary teams: *"Having enough self confidence to say 'I don't understand what you're saying. Maybe I'm stupid, but I don't get what you're saying.'"*

In the two-way interactive scenarios that formed the bulk of cross-disciplinary working environments, respondents consistently reported that creating supportive environments is critical. A team leader responsible for a large cross-disciplinary team states: *"Having a safe place to play, having a safe place to compare ideas, and no ideas are stupid, and an openness saying I don't have all the answers."* Even for highly experienced researchers who were placed on cross-disciplinary teams as a result of their expertise, discomfort from ignorance was laden in many responses. Table 13 shows responses from team leaders and a researcher with considerable experience working across disciplines.

Table 13 Addressing Discomfort From Ignorance

Experienced team leaders with cross-disciplinary teams:
- *"Helping people—I'll call it 'save face.' Don't embarrass people and back them in a corner. We all say stupid things from time to time. Nobody should be afraid to say what they're thinking. I'd rather have them say it and get past that, even if it's wrong, than to keep their mouth shut because they're afraid they say something wrong. I want their input."*   - *"The other person has to be motivated, willing to really sort of go out of their comfort zone to meet you somewhere in the middle, because you cannot go all your way to their comfortable zone."*   - *"There has to be enough mutual familiarity with somebody to understand that, okay, if I'm confused by what they're saying, number one it's okay for me to ask a question, I won't look like an idiot.*

Number two I understand that I might not fully understand the term you're using even if I think I know what it means. I have to be willing to think critically about it. It takes time to learn that. It's a skill."

Senior researcher with over 25 years experience:
- *"I was hesitant to say a whole lot in the beginning, because again, it was so much discipline [A] and I don't know discipline [A]. I don't want to be asking stupid basic [discipline A] questions. I realize I can't get them to be educating me about discipline [A] on these telecons. I'm going to hinder progress. This is maybe a very fundamental part of the whole multidisciplinary thing, is that the guy that's listening to the other person's discipline, he's constantly struggling to like, when should I ask? Because I really need to ask to understand this, and when should I just see how much more I can absorb and figure out because I don't want to ask about fundamental 101 in front of all these experts. Even though they probably would be okay with that, but you just never want to ask the stupid question in front of a big group of people."*

The example responses provided make it clear that mitigating discomfort and creating intellectually safe environments is an important facet of working across disciplines. Another important element involved addressing organizational "*isolation*" and "*distance*" by fostering "*co-location*." Respondents noted several means that were used to create a sense of cohesion in their dispersed team including collaboration rooms, business trips, and standing teleconferences at times convenient for multiple time zones; though many noted that face-to-face time was essential. A team leader describes his or her effort in creating "community" with a team of widely varying experts: *"I think that part of it really is trying to be able to form a community, and share that community, and grow that community, and make it a safe place where you can exchange ideas and nobody says 'oh, well that's stupid.' I think that creativity will happen."* Another respected senior researcher and team leader with 30 years experience also noted that proximity creates a sense of accountability:

"Let's say I optimize for [component A] performance. It's not like I'm not aware of some of the [related aspects from other components], but it's nothing like having a [person] in-house with me saying, 'Yeah, if you do that though, [Joe], they're going to [run up] against this. How about we do this instead?' Maybe I'll give up a little bit on performance because overall, I get a net better benefit. That dialogue up front helps. It's hard to do, partly because we have inherent natural fences, if you will, just by being in different offices, different buildings, different [sites]."

It is important to highlight that, as described by this respondent, typically the challenges associated with organizational structure are neither a result of engineering negligence nor incompetence of any person or role in the organization. On the contrary, most respondents were exceptionally skilled engineers or scientists and most managers had significant leadership and management training in addition to their technical skills.

A researcher with 40 years experience notes: *"part of it was just due to comfort zone since we didn't typically go outside our normal channels. It's an effort working with a completely different group, and getting to know them, and how to coordinate it all."*

From an organizational structure view, the boundaries created by line organizations and program structures are both explicit and implicit in nature. The implicit boundaries were openly noted by respondents and deeply rooted in and supported by the organization's culture. In addition, in many cases, respondents in the organization tended toward building thicker implicit boundaries than exist explicitly per formal organizational processes.

For example a line manager noted that one of the barriers to cross-disciplinary work is the need to go through *"official channels"* to facilitate the interaction between lines when no formal process exists. However, clearly, an informal process has been created and is likely re-enforced culturally. The comments of a young respondent with only a few years experience provides other evidence of boundaries that are culturally taught:

> *"Just the fact that you've got kind of these silos—you work with people in your [line] or this [line] or this [line]. You don't jump across those boundaries too often. There might be a few people that do that and then the [line managers] talk, but there's not just a common group of people that all work together."*

A senior team leader who strongly favors cross-disciplinary work concurred:
> *"Opportunities haven't necessarily been given to [discipline A] people to interact with [discipline B] or [discipline C]. (Interviewer: Why not?) Because we work in our own little disciplines. The projects are all segmented out."*

What is also highlighted in these observations is the limited human agency in working across implicit boundaries.

Boundaries are also imposed or re-enforced as protective mechanisms for the individual employee and the line manager. For the individual, an implicit boundary is sometimes created around their work as a form of intellectual and career turf protection. Creating their individual piece of work allows greater control, less ambiguity, clearer demarcations for identifying individual accomplishments, and a simpler path for becoming an expert in an area. In the survey, respondents noted protection responses as: *"protecting rice bowls," "ownership," "turf battles,"* and *"people get defensive of their 'little research worlds.'"*

For the line manager, the existing physical boundaries between line organizations are necessary boundaries within which they must operate. While most line managers are very supportive of the capability-based goals of the different programs, most of which stretch far beyond the work in their line organization, as leaders of a line organization their focus is necessarily on shepherding their line. Though they have no direct control of program funding, line managers have several significant organizational responsibilities, three of which are:

1) Ensuring that every employee in their line is fully funded by a program;

2) Maintaining high technical competence at a level sufficient for responding to current and future program needs; and,

3) Supervising employees and championing their careers through an incentive system that is largely single-discipline focused.

Hence, at times the line managers necessarily privilege maintenance of their line at the expense of proactively addressing more cross-disciplinary program goals. Several respondents who were team leaders that worked with many different line managers reflected on their views of the line managers' efforts as necessarily having a strong disciplinary focus:

- *"The desire for a [line manager] to make sure the staff is employed, ... and to keep their core competency. Because while we're working on this one thing, maybe this one competency isn't going to be necessary, but if you ignore it, then you either lose it or you just get kind of stagnant. [The line manager is] looking to where he sees need, to keep competency up, even though there aren't enough projects necessarily to provide that need now, but it's going to be necessary later. Project demands change over time depending on what the drivers are for the projects as well. It is a challenge. ... I see [line managers]—it's clear to me they're focused on keeping their guys employed: 'Can I have a fraction of [an employee funded] here and a fraction of [an employee funded] here?' "*
- *"A lot of the [line] managers only see the value in: 'What is going to care and feed my [line]. I need to cover my people and nobody else sees the world the way I do. [Our discipline is] the most important thing, and I want a big [discipline] program that just dumps money into [our discipline] so that I can do [work in our discipline].'"*

Moreover, as the line managers shepherd the employees, correspondingly, the relationship between the line manager and employees is much deeper than the relationship between employees and program managers who tend to be more cross-disciplinary than line mangers. Thus, the affinity of many employees is more toward

their (more single-discipline) line manager than their program manager. The resultant inherent tensions between 1) line and program organizations and 2) the competition for resources between individual line organizations both create two of the most critical boundaries for cross-disciplinary interactions. Table 14 provides a vignette from a line manager who illuminates the tensions.

Table 14 Vignette From a Line Manager Describing the Tension Between Integrating Across Disciplines and Shepherding a Line Organization

> *"There is a tendency for everybody to go their own way, do their own little piece. Give me my piece, and I will do my work. … The whole research system has been set up like that. Although we have these projects, but if you look at it, you start with a [very large project], you break it up into sub-projects. Then you split [the sub-projects] up into seven, eight tasks and so on. By the time you're down to [small-sized] tasks, which are not at all integrated with anything. … Basically what you have is each person running around as being their own project manager for [small-sized] tasks. …The whole structure is kind of not set up for encouraging multidisciplinary research. …How do you go about changing this whole structure? It has to take a few people who are willing to ruffle some feathers and stand up for what they believe is right.*
>
> *[Projects have] pieces of tsks, and they're all itsy bitsy tasks. They don't come up to anything combined. …the [discipline A] people want this piece of work. The [discipline B] people want this piece of work. Right now, we are project silos. [The researchers working in the projects, including my researchers] have to adjust. [Sub-project 1] has to work with [sub-project 2]. Ideally, this sub-project should deliver something to this sub-project, but there's no such interconnection. Is there going to be any deliverable from [one project] to [another project]? I don't know. The projects themselves become silos, and then the sub-projects beyond them become silos. If you want to have cross-disciplinary research, you've got to have deliverables across projects. …Right now, it's done by discipline. Okay, [discipline C], you get two [people funded]; [discipline D], you get two [people funded], because then everybody's happy and they do their own thing."*

Some respondents also noted a few proactive efforts in program management to encourage more efforts across the different disciplines or lines. While some programs remain focused on single discipline areas, many programs purposefully organize around interdisciplinary goals to avoid a focus on individual components or discipline areas. One senior researcher reports:

> *"Then every so often somebody comes in on high [in program management] and says 'I see too much stove piping. We're going to break it, cross it this way.' And we throw all the cards up in the air and we start all over. And then it kind of seems to gradually go back towards again more discipline orientated. I think it takes a conscious effort to break across that."*

However, as discussed in the chapter on organization culture, a conscious effort to work across the line organizations does not occur consistently.

In examining the boundaries in action resulting from organizational structure holistically, the data depicts a contrasting observation:

- Respondents (including managers and leaders) consistently argue that working across disciplines is important;
- Funding from some programs create a system-level, cross-disciplinary focus that sometimes includes organizing the program by system goals to avoid a disciplinary focus.

Yet:

- The discipline-based line organizations create a stronger focusing lens for organizational and social activity for line managers and their employees;
- Whether explicit or interpreted, the boundaries between disciplines are perceived to be *"structural,"* *"strong,"* and *"inflexible"* to a great deal of respondents in the survey, interviews, and ethnography.

The resulting bureaucracy is likely more static and constraining than intended by some organizational leaders. And, as the size and dispersion of R&D organizations for large engineered systems continues to grow, these characteristics may become more entrenched and difficult to adjust. Nearly all of respondents working in cross-discipline teams noted that members of their team were not co-located and had several different line supervisors, greatly increasing their communication and coordination challenges. The teams also include different external organizations such as academia, small business, large contractors, etc., all of which bring different boundaries and cultures.

Structure and Boundaries of Thought

While organization structure creates the physical and more explicit boundaries described above as well as implicit boundaries that can confine action, it also creates boundaries of thought that can have significant impacts on work outcomes. In this section, I created a fictionalized allegory to portray the findings from the data.

Lamp Allegory

Consider the following challenge: Conduct research on (or design) a lamp.

Though typically performance goals would also be set such as: improve lighting, efficiency, etc., by a certain percentage beyond existing concepts; as noted by many respondents, cross-disciplinary goals are very effective at triggering work across disciplines but yet markedly insufficient to overcome other obstacles in cross-discipline work. In this allegory, the organization doing the work may set up a typical hierarchical organization (depicted in Figure 7) where a company senior executive is responsible for the overall effort at the system level, which for this simple analogy is a lamp. The next level of the organization is arranged by parts of the lamp (shade, bulb, stem, and base). Each sub-organization is headed by a respective "part director." Each "part" organization is comprised of a group of engineers and scientists that address each aspect of the lamp development as organized.
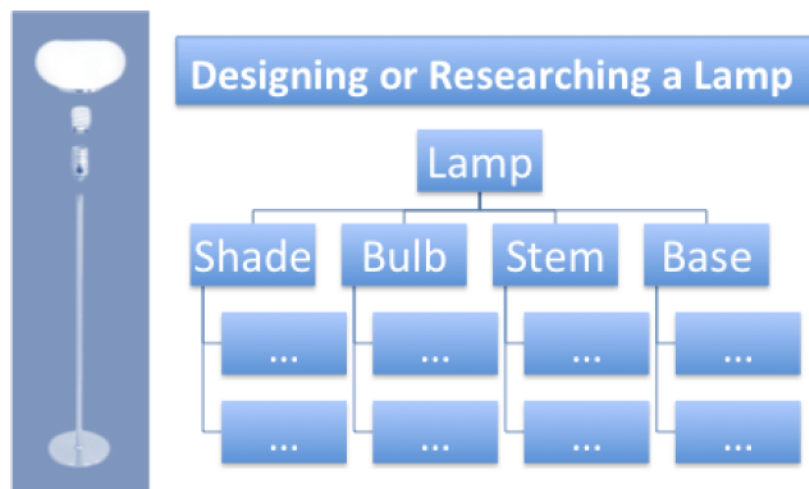
Figure 7 Graphical Depiction of the Lamp Allegory

Within each part group, R&D and early conceptual design are conducted and technology is advanced as is common in the line organizations discussed thus far. For example, improved filaments originate from the bulb group and enhanced shade materials are developed by the shade group, etc. In each part group, scientists and engineers conduct rigorous modeling and testing of many diverse technologies. Lamp part directors meet frequently to share recent results and exchange needed data

between elements, such as potential impacts of greater heat emanating from the bulb or the effect of different shade materials on lighting effectiveness. Systems analysis methods are also proactively used to determine which technologies would best address the objectives of the lamp program. As the better technologies reach maturity, a formal integration program is created and a systems engineering team proceeds toward advanced system (lamp) development.

Yet, consider a scenario in which one of the high performing system solutions uses an illuminating shade, exclusive of a separate bulb. Or, another high performing solution uses an illuminating stem, exclusive of a separate bulb (depicted in Figure 8). Attaining these unconventional concepts, or others that do not naturally derive from the traditional discipline experience, is extremely difficult or impossible, given the organization and the practices defined. These unconventional concepts are stuck between boundaries of thought created by the organization structure and related processes. The suggested unconventional concepts become essentially "unseen" by the scientists, engineers, and the leaders. Interestingly, words related to "seeing" were the most frequently noted action words of interview respondents after words related to "thinking" and "knowing."

Illuminating Shade
(no separate bulb)

Illuminating Stem
(no separate bulb)

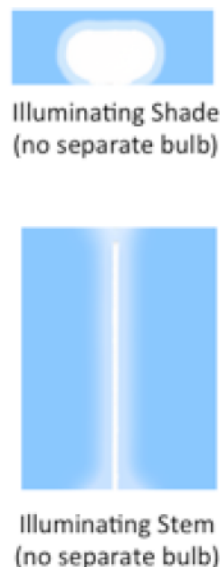**Figure 8 Unconventional Options from the Lamp Allegory**

It is important to reiterate that "missing" one of the suggested unconventional concepts is not the result of incompetence or negligence. Rather, excellence in executing respected, standard operating procedures and due diligence in R&D within one technical area is enabling as well as it is potentially inhibiting. Another insight is that examining any one of the suggested unconventional designs would exclude the work of an entire department. This creates a myriad of strategic challenges for the organization's leaders and employees.

In this example, the organization's structure and practices serve as a constraint on system design. Hence, the organization structure and practices can dictate the form of the resulting engineered system and limit the types of solutions created at all levels: technology, elements, and system. In a sense, this situation corresponds to the still elusive general problem in design: While we excel at refining and optimizing existing configurations (or system topologies), we have very few methods for creating new configurations or topologies — almost always relying on human creativity.

To address the lamp research, development, and design "challenge" described above, many organizational strategies have been created and are widely applied by many LaCES organizations. These may include:

1) Increasing the interaction between the "part directors;"
2) Increasing the guidance and mentoring provided by the "part directors" to their employees;
3) Further decomposing the parts of the lamp and increasing the detail with which the requirements or objectives are stated;
4) Increasing the fidelity of the physics-based tools and the accuracy of the experimentation related to each lamp part;
5) Hiring a systems engineer or optimization specialist or increasing efforts in these areas;
6) Requiring that all scientists and engineers document their findings on a knowledge management database.

Each of these strategies has merit and can provide important improvements in many engineering scenarios. However, none of these strategies would necessarily

break the boundaries of thought created by the organization's structure and practices. The essence of this conceptualization is the finding that organization structure can be highly influential to system research, development, and design. Organization structure often shapes the initial problem formulation, the content of meetings, the system requirements, and the technological solutions. In many technology-based institutions, organization structure is often assumed and ignored.

During the development of smaller consumer products, such as household electronics, many companies (such as IDEO,[119]) will co-locate a design team that encompasses diverse skill sets. This practice offers an effective approach to breaking pre-existing boundaries of thought and focusing attention toward the system rather than existing technologies. However, scaling product-development practices to large-scale complex systems development where hundreds or sometimes thousands of employees are needed is often irresolvable. In the discussion that follows, I will explore a few of the common large-scale complex system development strategies noted above more deeply, with attention toward their efficacy in breaking boundaries of thought.

Strategies 1 and 2

Several respondents noted experiences related to Strategy 1 (increasing the interaction of the part directors), expressing that it was important to have leadership and management model the desired interdisciplinary interactions for their teams. A line manager describes Strategies 1 and 2 in operation:

> "So the [upper management group] has meetings, and the [line managers] get together, and the [line managers] develop relationships and kind of know what the other [lines] do, so when they hear of a problem or hear of a research effort, then they can say okay, well we should go ahead and get people from this [line] to the table, and people from this [line] to the table, get people from this [line] to the table, and then we'll see, okay, how should this probably be addressed? Are there technologies already that will help us to address it?"

And, several respondents noted that they trust their line manager *"to point them in the right direction"* when needed (Strategy 2). Though line managers provide a wealth of expertise, increased discipline expertise can also guide efforts toward local

optimization.[6, 46, 120] Repko notes several challenges with increased specialization including: blinding one to the broader context of a problem; producing tunnel vision; failing to appreciate other disciplinary perspectives; worthwhile topics falling in the gaps between disciplines; and an ability to address complex problem comprehensively.[6] The literature on interdisciplinarity also notes that the challenges of disciplinary specialization are not met by eliminating specialization but rather by augmenting it as "The disciplines are foundational to interdisciplinary work because they provide the perspectives, epistemologies, assumptions, theories, concepts, and methods that inform our ability as humans to understand our world."[6]

<u>Strategies 3 and 4</u>

Strategies 3 and 4 are related and are exercised extensively in many industries. These methods are highly appropriate in many aspects of engineering; however, they are also insufficient for addressing unconventional solutions that don't naturally derive from existing solutions. Additional technical detail generally provides needed information in topics that experience has suggested is important; however, areas with little experience are often ill served with additional detail in known areas.

Strategies 3 and 4 also present a common approach in R&D centers where researchers will often focus attention toward improving "line-originated" technologies to address the greater system (the lamp). Technology maturity advances largely within a single "line" or area of expertise. Integration with other technologies from other "lines" occurs once the individual technologies have reached an appropriate stage of maturity. Or, researchers may work with other disciplines to mature and advance their technology as described in the previous chapter, where a single discipline becomes the focus of cross-disciplinary efforts.

The practices that surround strategies 3 and 4 rigorously advance the line technologies and often yield needed improvements to the system (the lamp). Yet this practice and the related "system view" is constrained by the implicit boundaries of the line in which it originates. One researcher with 30 years experience replies: *"We've each developed our own vocabularies and it makes it hard. We get so entrenched in our own way of approaching a problem that it makes it hard to understand what the*

other person doesn't know about the way that we see it and really communicate."

These practices also are also well supported by incentive systems that favor individual expertise. Researchers are incentivized to continue to advance technologies in which they have considerable experience and the greatest potential to demonstrate advancement within a line or area of expertise. An alternate approach to that of a "technology view that incorporates the system of which it's an element" is a "systems view that incorporates the technologies or expertise needed." In the latter, effort is placed toward system advancement, modifying and creating technologies as needed regardless of origin. Integration occurs simultaneously with technology advancement as described in the methods of *collaboration* and *collective* in the previous chapter.

Strategy 5

Strategy 5 is extremely effective for addressing many integration needs in the organization. However, the survey clearly showed a lack of significant mention of either MDO or systems engineering in working across disciplines. Interview respondents were probed for additional specificity regarding the manner in which MDO impacts their cross-disciplinary interactions. All respondents respected the work of the MDO groups in their organizations stating that it was essential for understanding some systems-level trades. Respondents stated that the systems-level analysis conducted by the MDO groups helps increase awareness of the impacts of disciplines outside a researcher's specialty area and is helpful for assisting program managers in determining the allocation of resources for different technologies.

However, most respondents noted that MDO did not typically initiate cross-disciplinary interactions, but rather was sometimes helpful in analyzing the sensitivities of different technologies within a cross-disciplinary effort. A single-discipline researcher with 30 years experience conveyed that MDO: *"helps because when I understand what about the other person's activity or discipline is important especially from the global perspective. Then I can better appreciate it and I can try to understand when I should try to work with them a bit more. Help them a bit more. Or else to just understand the whole problem in general. That sometimes spawns a new idea, actually."*

Regarding evaluating unconventional concepts, several single-discipline

researchers stated that MDO was less effective in this area. One of the chief challenges in working with unconventional concepts with MDO that respondents (both MDO researchers and single discipline researchers) stated is a mismatch in fidelity between single-discipline researchers and MDO and systems analysts. Where MDO and system analysts need low fidelity models in order to efficiently evaluate a system, yet the researchers are working toward higher fidelity in terms of modeling and understanding the new technology. The challenges here are multifaceted, frustrating both MDO researchers and single-discipline researchers. A few of these challenges are summarized below.

1) Lower fidelity models are not of interest to many single-discipline researchers as many view them as a step backwards in technology maturation. This creates challenges with career advancements and peer respect in the single disciplines and it stymies progress in MDO.

2) The lower fidelity information needed by the systems analysts may be based on parameters from conventional concepts, which may not capture the principal benefits of the new technology developed by the single-discipline researcher, which discourages the single-discipline researcher who would like to more fully use the capabilities of their new concept. However, the single-discipline researcher may not fully know how to create a model that is appropriate for MDO research.

3) As noted earlier, there is not significant incentive for the single discipline researcher to take the effort to create a model for interdisciplinary design.

4) Cognitively, the MDO researchers and single-discipline researchers are often focused toward different directions. Referring back to the two cultures described in Table 6, the MDO researchers mostly work towards design and many single-discipline researchers work towards analysis.

Many respondents, both MDO researchers and single-discipline researchers, emphasized the challenges noted above. These challenges create a communication and cognitive gulf between MDO researchers and the single-discipline researchers. In essence, the two parties are speaking different disciplinary languages, working at different fidelities, and have different understandings of the technologies and the system they would be integrated within.

The lack of reciprocity (mentioned in the previous chapter) in the relationship between MDO researchers and single-discipline researchers adds to these frustrations. Nearly every MDO researcher expressed frustration in obtaining sufficient information from single-discipline researchers for conducting their analyses, while single-discipline researchers noted there were difficulties in working with MDO to address unconventional technologies. MDO researchers state that they are constrained by the codes, performance data, and support they obtain from single-discipline researchers. With an incentive system focused toward individual achievements, many MDO researchers and single-discipline researchers note that there is insufficient incentive for single-discipline researchers to proactively work with the MDO researchers. All of the MDO researchers were enthusiastic and even passionate about working with unconventional technologies; however, incentives, existing codes, and communication were often constraining. More discussion on the impacts of engineered system structure will be discussed in the next section. Table 15 displays example responses from single-discipline researchers in working with MDO researchers to address unconventional technologies.

It is possible that the cognitive gap between the MDO researchers and the single-discipline researchers may be a significant source of the frustrations mentioned. While the MDO researcher may have an advanced understanding of the system with limited understanding of the new technology, the single-discipline researcher has an advanced understanding of the new technology with limited understanding of the system – and, the incentive system encourages the latter. Marrying these two areas of expertise requires an interdisciplinary knowledge integration where both groups interactively and reciprocally update and modify their incoming understanding and change their theories and methods as necessary. However, often respondents described a multidisciplinary (not interdisciplinary) integration scenario where different single-disciplinary researchers independently provide information to an MDO researcher who integrates the different inputs. In the scenarios observed, the MDO researcher may have an increased interdisciplinary understanding of the varying disciplines and the system; however the single-disciplinary researchers may not. Many of the single-disciplinary researchers that supply the MDO research group with information do not

interact between themselves.   Thus, while they might update their single-disciplinary models with new data from the MDO group such as new boundary conditions or system operating conditions, their single-disciplinary understanding, knowledge, theories, and methods may not be significantly modified.

Table 15 Four Single-Discipline Researchers, each with 20 or More Years Experience, Describing Working with MDO Researchers

- *"We have a very nuanced multi-dimensional world and trying to take all this vast subtleties you understand and try to collapse into something that you can pass up and it can be used and not misrepresented at the system level. That's the pain and the cost to working that."*
- *"They're looking at too high a level. I'm looking down at what's happening at [a significantly lower] level. They don't even care if I've got [A], [B], and [C], or if I've got [D]. So, from a [discipline X] world there's a huge difference in how you [work that technology] and how that actually performs. Because the systems level guys are looking at the [whole] system, they've simplified all of my problems down to—or all of my solutions down to a single problem to the point that it's oversimplified. So, they're not capable of giving me [trades on our technologies]."*
- *"I still don't know if that [MDAO] goes down and captures everything. You know with MDAO, you're kind of looking at a suite of tools that may be pre-existing, or existing and they may not fully capture all of the various disciplines. ….[such as] other technologies that they might be able to pull in and integrate to arrive at another solution. … in terms of looking at what's out there and what's emerging, and integrating all the different technologies together, I think, is different from doing a [model-based systems] analysis."*
- *"If the systems analysis person jumps to a conclusion without having enough information—I think systems analysis people probably tend to have a fairly broad perspective, I think, because they've had to work on a lot of different stuff. It becomes tempting for that person, I think, to feel that I have a perspective and I can probably tell sooner than those specialists that they're going off on a track - it may be fine for them, but it's not going to fly. I think this may be tempting for a systems engineer to make—not quite snap judgments, but too early judgments on things."*

Strategy 6

A few researchers and several managers suggested the knowledge management approach in strategy 6, seeking increased awareness of the breadth of work being conducted in their large organizations.   Knowledge management is one of the many topics that are associated with but beyond the scope of the current study.   When asked

what kind of data researchers needed in working across disciplines, many noted that what they really need is time to think, understand, interact, communicate, and build relationships.

In studying the challenges for distributed, interdisciplinary teams, Haythornthwaite et al, note that while much literature and organizational effort is focused on making "tacit knowledge explicit for transfer to others" their research suggests that "contemporary teams face a more complex set of issues as they engage in joint knowledge construction. Contemporary team members find that cannot simply transfer their previous collaborative skills to a widely distributed, interdisciplinary arena, but must continually renegotiate a wide range of research and work practices thought to be already established." Their research also distinguishes novices and experts suggesting that while novices may focus on "transfer," experts on distributed, interdisciplinary teams focus on "joint problem-solving, shared cognition and co-construction of meaning."[12] The importance of interaction to enable knowledge transformation and greater understanding is underscored in numerous literature as noted previously.

Respondents also reported that cross-disciplinary efforts sometimes originate from individual researchers taking initiatives and making the needed cross-organizational connections. A line manager reported:

> "Sometimes it bubbles up from the bottom up, and sometimes it trickles down. I was part of a project where a guy who was in the [discipline A area]. He said, 'Hey, this would be really something cool to work on.' So, he went around and talked to people that he knew who were in the different areas, [discipline B], [discipline C], and other areas, and [discipline D]. He said, 'Hey, I've got this real cool project. Would you like to work on it?' Everybody said, 'Yeah, that's cool. Let's work on it.' So, he basically—it was like a self-forming team. Because everyone thought that the challenge was cool, something that they could apply their expertise and skill set to, and it actually was very, very productive. So, that was something that bubbled up from the research involved."

Discussion on Organizational Structure Impacts

The lamp allegory illustrates how the engineered system concept is a function of the organizational structure and practices such as software configuration, incentives, program structure, milestones, etc. The structure of these practices can dictate the

form of the engineered system. The significance of this finding is that most engineering organizations do not assume that organization or program structure has an appreciable impact on engineering and scientific outcomes. In the example allegory provided, managers and researchers quickly set up a research effort based upon traditional departmental competencies that have historically yielded effective systems (in this case, lamps). However, systematically linking together well-known disciplines may not create opportunities for discovering or developing significant enhancements in the system configuration or performance desired, regardless of the quality of work in the disciplines.

The preceding discussion additionally provided an example of how the engineered system is impacted by the initial problem formulation, which is often accepted as given rather than researched or designed. An alternate approach to framing the research or design challenge in the allegory is: "illuminate the room" or "provide light to enable a comfortable working environment." The discussion borne from these top-level re-framed goals may provide useful triggers for cross-disciplinary interactions. Several researchers in the interviews repeated that visionary, crosscutting system goals were a positive trigger for encouraging cross-disciplinary work.

Implementing any of the strategies mentioned (and possibly others) without further complementary actions, such as addressing the social challenges and incentive system impacts noted earlier, will likely fall short of fostering the development of the unconventional solutions presented. It is possible that though interdisciplinary interactions are valued, and integrated teaming is quite common, the organizational "system" may be structured to support efforts that are more singular in nature.

Impact of the Structure of the Engineered System

Thus far, I have discussed several organizational factors that influence interactions between disciplines including culture, processes, and structure. Four principal methods of combining disciplines and two prevailing engineered system perspectives have also been presented. In this section, I explore influential factors of the engineered system itself. As with the topics previously discussed, social and cognitive factors are inextricably tied to the discussion.

Data revealed the following theme: the format or layout of the engineered system can also drive and even confine interactions between disciplines. This finding emerged as respondents repeatedly framed their comments based upon the format or layout of the engineered system. To explain this finding I will use a conceptualization entitled a "Suite of Similar."

Description of Cross-Disciplinary Work Practices in Suites of Similar Architectures

Though the focus of this investigation and the foundation of all findings are for very large, complex engineered systems such as aircraft or submarines, the simple lamp example previously presented will be used as an analogy in this discussion. However, the large size and geographic dispersion of most R&D and early design teams should be continually kept in mind, as many of the challenges discussed subsequently are mitigated or eliminated for small, co-located teams with established relationships.

I begin by defining two expressions that are central to this discussion: system architecture and Suite of Similar. For all engineered systems, a notional configuration is typically identified to commence R&D efforts. The "configuration" is also known as the "system architecture" or "system layout" or, in program management or systems engineering, it is the "work breakdown structure" or "WBS." These terms all relate to how the engineered system is organized or structured. For example, in the allegory previously presented, the initial system architecture for the lamp was: shade, bulb, stem, and base (Figure 7). The unconventional system solutions presented used a different system architecture for the same system goals: shade, stem, and base (Figure 8). The architecture is defined not only by the major elements of the system but also by the manner in which the elements are combined.

A 'Suite of Similar' is a suite of similar system architectures. Particularly for large systems, engineering design typically does not create a completely new system, but rather the system design is often a derivative of an existing system design – often adopting a similar architecture to the original system. For example, for the lamp, the Suite of Similar system architectures of "shade, bulb, stem, and base" offer innumerable

lamp designs of great diversity allowing for a variety of research and development efforts while yet working within the existing Suite of Similar.

Most engineering organizations including academic institutions are structured to teach, research, develop, test, and design within a Suite of Similar system architectures and the respective system elements. For example, for metal aircraft structures, a semi-monocoque, stressed-skin architecture of ribs, spars, stringers, and skins is known to be highly effective and efficient. Thus, the work of students and practitioners focuses on learning and improving ribs, spars, stringers, and skins.

In this conceptualization, I abstract two types of Suites of Similar: an Existing Suite of Similar and an Emerging Suite of Similar. The conventional lamp architecture is defined as an Existing Suite of Similar and the unconventional lamp architecture of shade, stem, and base is defined as an Emerging Suite of Similar. For most research, development, and design, a system architecture (a Suite of Similar) is defined upfront. Emerging to a new Suite of Similar takes considerable effort and changes to both practice and thinking.

Often, when presented an opportunity for a new, Emerging Suite of Similar system architectures due to new technological advances, many engineers return to the work practices and the architecture of an Existing Suite of Similar. Klein, et al, also report a tendency for engineers to "stick near well-known designs"[36] For example, instead of taking full advantage of the capabilities of graphite composites, many composite structures for aircraft are built using the ribs, spars, stringers, and skin architecture that was defined and optimized for metal structures ("black aluminum"). While this approach is not an engineering optimal solution for using graphite composites, it may be an organizational and cognitive optimal solution due to familiarity with the Existing Suite of Similar.

A few salient points of the findings on Suites of Similar architectures are: Existing Suites of Similar define most work practices as well as cognition – enabling efficiency while constraining cognition. Cross-disciplinary practices are very different for an Existing versus for an Emerging Suite of Similar. Pointedly, the Suite of Similar defined or adopted by engineers defines and demarcates a great deal of the cross-disciplinary practices and understandings in an organization.

The majority of work practices are defined by the needs of Existing Suites of Similar system architectures including departments, meetings, incentives, and mathematical models. The primary disciplines and their primary interactions are typically known for the Existing Suite of Similar. Thus, when working with an Existing Suite of Similar, practitioners generally know how to interact with other disciplines. In an Emerging Suite of Similar, practitioners generally do not. Two researchers with more than 30 years experience explain:

- *"In a traditional [system] we kind of know what that looks like. Like the [element A] guy knows how to talk to the [element B] guy and they kind of work together. The [element C] guy knows how to do the layout and he prescribes it. That's a well-established process."*
- *"It's the system you're trying to design. If you're just designing [within an existing, known system architecture] you don't really need a whole lot of cross-disciplinary interaction. There are some areas of the [system] where you need them but for the most part you can design [element A] independent of [element B] and [element B] independent of [element C] and the [element C] independent of [element D]. If you're designing a [new system with different architecture] you can't account for that."*

In the Emerging Suite of Similar many previous assumptions, practices, and heuristics may no longer be valid. The existing work practices that address the needs of Existing Suites of Similar are inhibiting for some or all of the needs for the Emerging Suite of Similar. The emerging suite of new system architectures does not necessarily have more couplings nor is it necessarily more complex than an Existing Suite of Similar; rather it has different couplings and different cross-disciplinary interactions – which confuses traditional practices. Researchers and conceptual designers are unsure where system elements can be separated and are unsure about the extent of element and disciplinary interactions.

The Emerging Suite of Similar may not be easily separable cognitively or physically until greater system understanding is developed. Hence, understanding of the system in the Emerging Suite of Similar has to evolve. At the early stages of working with an Emerging Suite of Similar a respondent notes: *"An [element A] solution by itself wasn't going to [address the system goals like it used to]. You have to do an [element A] solution with an [element B] solution, and there's going to be interaction, and the systems end up becoming so tightly coupled that you can't separate."* It is

possible that eventually the new Emerging Suite of Similar that this respondent is working on will eventually be an Existing Suite where the couplings are known sufficiently to separate the work again. However, as noted by another respondent, sometimes disciplines are forced to merge or fuse in an Emerging Suite of Similar in such a way that: *"If you put an [element C] embedded inside [element D], the whole [system] now becomes [one large, fused element], so you can't now just completely separate [element C] from the rest of the [element E dynamics].* Many respondents noted that they did not know how to separate the work in an Emerging Suite of Similar, thus: *"You're going to have these potential solutions that you need [in order] to get to your goals that can't be realized unless you go through that multidisciplinary, cross-disciplinary analysis with everything working together."*

The new architecture and respective delineations of an Emerging Suite of Similar emerges from interdisciplinary interaction – it is not given. Even a notional or draft new Suite of Similar that is envisioned and drawn for the sake of initiating new ideation and fostering communication and creativity is yet to be fully defined cognitively. A deeper understanding of the internal elements and the system responses emerges through a co-construction of knowledge and understanding between researchers. The co-construction of knowledge and resulting understanding of the system and its cross-disciplinary interactions are central to the Emerging Suite of Similar. Existing and readily available information on the system and its cross-disciplinary interactions are central to the Existing Suite of Similar where a breadth of literature and academic study provide a basis of understanding. Also, existing organizational and social connections may be based upon Existing Suite of Similar.

An MDO researcher with over 30 years experience describes some of the challenges working with an Emerging Suite of Similar:

"For them, they're taking a somewhat known design and just tweaking it a little bit, and [high fidelity codes are useful to addressing known areas]. We need something to say, 'Here's a new configuration, roughly what the geometry characteristics are; here's what the performance might actually be.' Or, we have some really unique things, [such as X, Y, Z]. There's no data on that; there's no modeling tools for that. We can't go through and estimate the performance with anything that we have and it's outside of our knowledge base, I guess, in terms of what was historically done. We've just struggled with that."

One of the core challenges in working with an Emerging Suite of Similar is that the available guidance from experience or existing system architectures provides information of limited use. For the analogy provided, for example, attempts to utilize the technical requirements for light bulbs in order to advance the development of illuminating shades may be both helpful and counterproductive. The working environment of the Emerging Suite of Similar is that of *collaborations* and more likely *collectives,* where diverse teams convene cognitively to interactively construct the emerging system architecture and its engineering elements.

This is a scenario where complete awareness of next steps is elusive and the existing data is ambiguous. With ambiguity (or equivocality) "participants are not certain about what questions to ask, and if questions are posed, the situation is ill-defined to the point where a clear answer will not be forthcoming (March and Olson 1976)."[75] The engineered system in the Emerging Suite of Similar is fundamentally underdetermined. Although intelligence is high, ignorance is inherent. And, as noted previously, the data reveals a strong tie between ignorance and personal discomfort. Hence, working with an Emerging Suite of Similar creates high cognitive and social needs, the latter of which is further strained by large, dispersed organizations. As the work in the Emerging Suite of Similar is closer to that of a collective, the literature noted earlier on collective mind and sensemaking are used for analysis. An MDO researcher provides a descriptive vignette in Figure 9 to illuminate interactions and cognitive challenges in working with an Emerging Suite of Similar.

Figure 9: Vignette from an MDO Researcher Working with a Cross-Disciplinary Team to Develop an Emerging Suite of Similar Architectures

"If you're working with a [discipline A] guy, typically they understand that there's a certain [constraint] that they have to [do their work within] so they can't exceed anything. They're not used to [doing their work in the new way we're asking]. They usually [do it this way]... So when [we ask them to do it the new way], what typically was never an issue … starts to become an issue. Well the [discipline A] guys aren't used to thinking that way so their entire design process in their head is 'I'm going to design [my Element A], and I'm going to do this, and this, and this.' All of sudden we need to make sure [that we change Element A to address something new].

That's a very [interdisciplinary] problem. It's not one that's typically considered at an early design stage, but when you're dealing with a [new system] that needs to have [Element A done differently] because that's what it has to be, then you have to consider some issues you've never considered before. Whether or not you can get the [discipline A] guy to realize that his design is going to have to incorporate that.

Sometimes you get people in a room who just say 'Well, I can't design it that way. It can't be done and that's not how we design things and we don't have any empirical knowledge that way.' It depends on whether it's inside their designer comfort zone or not. Engineers tend to have an

> *empirical understanding—an intuitive understanding—of whatever system they're trying to design. It's good. They design lots of them so they should. If the system moves too far outside their understanding, they either try and force it back in or recognize that they're going to have to go against their intuition as to how a system's going to look.*
>
> *If you're just throwing a lot of disciplines at a traditional [system] then, it doesn't matter, their intuition's going to be right anyway. They know it's going to work. They know how [Element A] is going to look. It doesn't matter. If you're throwing a bunch of disciplines at a problem because it's unconventional and you expect the answer is going to be different than your intuition, then if you've got a bunch of designers in the room that want a design to what they're used to seeing, it's going to be very difficult to get an answer out of them because the answer's not going to be inside their typical comfort zone. If you're not willing to look outside that from a design process point of view, you're not going to get a design that's outside your comfort zone.*"

In examining the findings on Suites of Similar I note several principal themes: the Emerging Suite of Similar is constructed not given; practices, as well as organizational structure and culture, that are effective for an Existing Suite of Similar may be counterproductive for developing an Emerging Suite of Similar; ambiguity and ignorance are dominant in working with an Emerging Suite of Similar; uncertainty and awareness are dominant in working with an Existing Suite of Similar; and many organizational leaders and managers are unaware that they are steering their employees toward and measuring progress by the Existing Suite of Similar, though they may actually desire a new system design with an Emerging Suite of Similar.

Literature on distributed interdisciplinary teams, notes: "contemporary views that consider technology as providing the solution to the 'problem' of collaboration – e.g., through faster connection, seamless integration of geographic distributed people and projects and new information and communication technology infrastructures – fail to acknowledge the negotiation of practices and coevolution of practices and technology that are involved. Collaborations involve dealing with existing practices, as well as emergent ones that take time and effort to evolve."[12] In the following extended table (Table 16), I contrast the practices and challenges of an Existing Suite of Similar versus an Emerging Suite of Similar.

Table 16: A Comparative Summary of the Practices and Challenges of Existing and Emerging Suites of Similar Architectures (Source: the Author)

Existing Suite of Similar Architectures	Emerging Suite of Similar Architectures
System decomposition is known and defined by elements with little known coupling. - Overall architecture remains mostly the same throughout R&D and early design, or it is further optimized - Elements are improved over time. New technologies are added and the elements re-optimized	System decomposition is notional with lack of clarity regarding how to organize or architect the system due to uncertainty of where major couplings lie. - Overall architecture and definition of system elements remain provisional for an extended period of R&D. - New technologies add capability and confusion.
Major interactions between elements are known and mostly understood.	Major interactions may be unknown and not well understood.
The organization and its practice are likely structured to foster the interactions appropriate for the Existing Suite of Similar resulting in less needed cross-disciplinary interactions by design of the organization and its practices. Existing bureaucratic hierarchies may be effective.	The existing organization and its practices may not be structured to foster the interactions needed for the Emerging Suite of Similar resulting in more, as well as different, cross-disciplinary interactions. Existing bureaucratic hierarchies may be inhibiting.
Cross-discipline practices are mostly known. Sensemaking is more accurate: what cues to stress and what cues to ignore are largely known. - What to act on is mostly known including: Who to work with, What data is needed, What levels of fidelity are important - What to ignore is mostly known including: What is unnecessary or what is unimportant scientifically. - Meeting facilitation, and program or team planning, is more straightforward. Size and dispersion of teams is less of an issue since the extent of interactions is more defined. - External practice supports and enhances internal practices: Conferences and other external practices are organized around the Existing Suite of Similar	Cross-discipline practices are not clear. Sensemaking is encumbered: unsure what cues are important and what cues to ignore. - What to act on must be defined: Who; What data; At what fidelity - What to ignore is ambiguous: Not necessarily a lack of sufficient information, but rather equivocality in the information at hand and ambiguity regarding what is else is needed. - Meeting facilitation, and program or team planning, is more open-ended. *"Feeling like we are going no where."* Size and dispersion of teams complicates the high interactive and social needs. Wider and more proactive networking may be necessary. - Improvising new practices
System elements likely derive from existing disciplines. - Discipline expertise provides guidance for defining system elements and interactions	System elements may not naturally derive from existing disciplines. - Discipline expertise may be helpful, as well as counterproductive in defining the elements of the Emerging Suite of Similar. - Some of the disciplines essential for the Existing Suite of Similar may be used very differently, minimally, or may be eliminated in the Emerging Suite of Similar
A focus on elements may be privileged over interactions due to element boundaries being defined by regions of minimal interaction or coupling. - Focus is directed toward system elements more so than interactions due to an advanced understanding of element interactions. - New directions for R&D are usually within an	Elements boundaries and definitions emerge from examining interactions or their lack - Interactions are privileged over existing elements in order to define new elements effectively. Not necessarily more couplings but different couplings and interactions - The new elements are defined by the interactions (or their lack)

existing technical competence
- Known – Unknowns (Awareness):
  ▪ Challenges of uncertainty dominate with fewer ambiguities
  ▪ Fidelity within a discipline is usually the focus
	- New areas of expertise may be defined based upon the new elements and interactions of the Emerging Suite of Similar. New directions for R&D may be orthogonal to traditional R&D directions
	- Unknown-Unknowns (Ignorance):
	  ▪ Challenges of ambiguity dominate with uncertainties being less important until ambiguities have been resolved
	  ▪ High fidelity models of elements or interfaces are not necessarily required; rather, greater understanding of the interface dynamics and elements may yield derivation of sufficiently accurate lower fidelity models.

Typically begin work practices with system decomposition, then focus on the elements, and then address interactions as needed - Clarity, awareness, and understanding facilitate selecting and tailoring work practices effectively and efficiently. Methods for combining disciplines can be selectively chosen as needed: *connecting, coordinating, collaborating*, and a *collective* - Integration naturally occurs much later in R&D - Existing system-level methods such as MDO and system engineering can be very effective, as considerable empirical data exists. Problem formulation, objective statements, and requirements are assumed to be given upfront and adjusted over time.	Likely need to begin with *collaborative* and *collective* practices to understand interactions and identify major elements, then the earliest provisional architecture may be updated. - May start with a *collective* or *collaboration* and define *connections* or *coordinations* as work proceeds and understanding increases - Creating the system decomposition/architecture along with the elements. The earliest, provisional system specifications do not depict all of the interrelations of the final system as these are derived not given. - Integration may be the focus of the R&D efforts beginning at system conception - Existing system-level methods from MDO and systems engineering may or may not be helpful. Problem formulation, objective statements, and requirements are co-constructed by interdisciplinary interactions of the team.
Cognitively: Awareness prevails and disciplinary knowledge is honed	Cognitively: Ignorance prevails and disciplinary knowledge is modified
Socially and emotionally: Existing networks and relationships may be sufficient making interactions more comfortable	Socially and emotionally: New networks and relationships are needed and are marked by ignorance making interactions more discomforting
Organizationally: Existing roles and responsibilities more clearly facilitate the needs of developing the Existing Suite of Similar	Organizationally: Existing roles and responsibilities may be confusing and potentially inhibiting in trying to facilitate the development of the Emerging Suite of Similar; improvising and organizing are ongoing

Discussion on the Work Practices of the Suites of Similar Architectures

Much of existing practice is determined by Existing Suites of Similar system architectures where cross-disciplinary needs are better defined. Though new engineered system architectures emerge slowly, they often change ahead of organizational processes and engineering practices. Many respondents, managers, and leaders genuinely desire to create innovative and unconventional system solutions

in Emerging Suites of Similar. However, significant data in this study showed that most are unknowingly constrained by practices that re-enforce Existing Suites of Similar.

For example, existing mathematical tools, organizational structure, program structure, requests for proposals, incentives, and the composition of standing meetings, teams, etc., may be based on Existing Suites of Similar, which allows for important innovations within the Existing Suite of Similar, but can create boundaries of action and thought that inhibit discovering and developing Emerging Suites of Similar, as depicted in the Lamp Allegory. Haythornthwaite et al note that: "to an expert, disciplinary, institutional and personal research practices are deeply ingrained and often invisible."[12]

The order of some systems-level analysis methodologies may be dissimilar between Existing and Emerging Suites of Similar. For example, as noted in Table 16, for an Existing Suite of Similar, beginning R&D and early design efforts with system decomposition along lines of known minimal coupling in order to demarcate the performance needs for individual elements and disciplines may be appropriate. This approach allows research teams and mathematical models, organized by system element or discipline, to be formed and updated, respectively. Methods of combining the differing elements and disciplines may be driven by known system needs or organizational procedures where *connections* may be sufficient for lightly coupled elements and *collaborations* may be needed for more multi-functional, coupled areas of the system. Rigorous, physics-based MDO methodologies can be used to integrate and optimize the elements for system-level performance goals by addressing element (and disciplinary) interactions through existing mathematical models.

For an Emerging Suite of Similar, this process may be reversed. As remarked by Simonsen et al: "Design work in organizations is about negotiating arrangements and is characterized by co-production, translation and bricolage. …The realized design is an outcome of planned as well as emergent activities."[121] An Emerging Suite of Similar is characterized by more emergent rather than planned activities, where an Existing Suite of Similar may be sufficiently developed by more planned rather than emergent activities.

For instance, identifying areas of minimal coupling in a potential emerging system often requires expertise from different disciplines to convene *collectively* or *collaboratively,* first to facilitate the co-construction of system understanding then subsequently, defining decomposition and element requirements or objectives. This highly interactive and interdisciplinary early work is inherently emergent in nature where "the goal, purpose, or result of the research process is to construct a more comprehensive understanding."[6] From this evolving system understanding, new practices, elements, and even disciplines can be created. The following excerpt from Simonsen et al describes this process well:

> Since design work involves 'inquiry into systems that do not yet exist' (Romme, 2003: 558) and thus uncertainty about what 'will work' in a specific problem situation, emergent behaviors are especially important when doing design work. Following Mintzberg and Waters (1985), emergent strategy does, however, not mean that designers are out of control, only that they are open, flexible and responsive, that is, willing to learn. Openness to emergent strategy enables designers to act before everything is fully understood - to respond to an evolving reality rather than having to focus on a stable fantasy. Emergent strategy or design implies learning what works - taking one action at a time in search for a viable pattern of consistency (Mintzberg and Waters, 1985:15).[121]

Several respondents described similar experiences where they went through a learning process, updated their thinking, and then updated their work practices accordingly. In the following example, two respondents provide examples their similar experiences of updating knowledge and improvising work practices. Both of these respondents are single-discipline researchers with over 30 years experience who work extensively in cross-discipline teams:

- *"When you're going into cross-disciplinary you don't understand their discipline enough to really specify that well. After you work around they're like 'Oh you want that? Then oh, we need to do this.' [or] 'Oh, I didn't know that. Well, okay, now we know what we need."*
- *"Then you learn from them [the other disciplines]. Then of course maybe some of their first suggestions back to you may not really fit. You go 'Oh wait a minute. Naw, that doesn't quite do this for me. I'd forgot to say I need to do this.' Some of your requirements weren't quite born out till you go back and forth. You have to kind of go back and forth to fully flesh out."*

Thus, instead of following existing engineering practices of beginning with 1) system decomposition to identify elements and respective engineering disciplines and requirements, then 2) focusing on developing and maturing system elements and disciplines accordingly, followed by 3) an integration of elements when disciplinary understanding is mature — work practices for an Emergent Suite of Similar begin with 1) interdisciplinary interactions to understand what the system and its elements may be, and this *collective* understanding can eventually lead to 2) identifying the best manner in which to combine elements and disciplines whether those combinations are *connections* between lightly coupled elements or *collectives* of highly fused elements.

Requirements as Co-Constructed not as Given

In particular, requirements definition is typically an essential aspect of beginning new research, development, and early design. However, cognitively, the requirements do not supply sufficient information and likely the wrong information for working in an Emerging Suite of Similar. I will examine an extended vignette from one respondent to elaborate on this finding. This respondent is a single-discipline researcher with over 25 years experience that works extensively in cross-discipline teams usually serving as the team leader.

This respondent notes that: *"The external constraints were numbers. They were just a set of requirements, but I don't understand where those requirements came from or the context. So, all I put into it is meeting those requirements."* The requirements that were provided to this respondent and his/her cross-disciplinary team were standard performance goals and operational parameters that had been used for a considerable time and updated in detail for a new system development effort. However, this respondent reports that a deeper understanding of the rationale behind the requirements was necessary. *"So, what I've seen as I've moved towards understanding the other disciplines even just a little bit, understanding the application, is realizing that my [discipline] can influence a lot more than the set of requirements that you gave me. So, the set of requirements was what you thought I needed to know."*

The respondent identifies that the requirements provided were likely derived from an Existing Suite of Similar.

"So, in the deep dive [single discipline] research you're trying to focus on the requirements people have told you about. You're missing out on the requirements that nobody told you about. So, in that deep dive you can continue to define to a 'gnat eyelash', the [parameters of your element]. I can have… the [best properties] in the whole world, but [these parameters] aren't the only things I need. So, the risk in just the deep dive is that you're limited by the requirements that somebody has given you and the information that somebody has given you."

Here the respondent describes being limited by the requirements that were provided. The respondent was very clear in stating there was not an insufficiency in the detail in what was provided, but rather an insufficiency in the understanding of what was really required or, more importantly, what was really desired. Arias et al describe that "having different viewpoints helps one discover alternatives and can help uncover tacit aspects of problems."[63]

"So, without understanding some of the other system needs, big system needs, you can't take advantage of [additional] functionality, not very easily, and you can't design for [additional] functionality because you don't know that oh, this is also a requirement but it wasn't anything anybody told you was a requirement because maybe they didn't know it was a requirement."

The evidence of unavoidable ignorance is portrayed in this quote where there is an unknown requirement that can only be discovered through interdisciplinary interactions. Engineers often speak of "unknown-unknowns" during system development. Taking this vernacular and concept a step further (and stretching grammar), the finding here is that ambiguity and ignorance create "unknown-can't knowns" in the system that cannot be addressed by traditional means of adding more data, more fidelity, more computations, etc. Rather, the integration required in developing an Emerging Suite of Similar is an interactive and cognitive integration. Klein writes of this in the following:

"The communicative competence needed for interdisciplinary work is inextricably bound up with problems of language….Any interdisciplinary effort requires analyzing definitions and terminology in order to improve understanding and construct an integrated framework (Glantz and Orlovsky 1986, 215; Bennett 1986, 347). … Computers undeniably are valuable tools when dealing with aggregate data sources, multivariate databases and archives. Yet even powerful software and proven techniques such as… common data analysis, system simulation, and theory construction do not guarantee that synthesis will occur (Klein 1990-91, 39). Integration is a human action. The result, synthesis, is negotiated, situationally

dependent, and contingent on the participants."[46]

Traditionally, in engineering, integration is viewed as an effort of uniting physical hardware or computer software. The interdisciplinary interactions of the Emerging Suite of Similar and its *collective* action require cognitive integration that draws from many different disciplines and experiences. "The individual brings to the situation his or her repertoire of skills, knowledge, and strategies, which affect and are affected by the situation."[57]

As noted, knowledge is enacted and is constructed through continuing interaction. It is important to clarify that while *collective* knowledge is necessary to develop the Emerging Suite of Similar (and usually several aspects of the Existing Suite of Similar as well) – its status is provisional and dependent on ongoing interaction. As the differing disciplines and organizational units advance in system development over time, new insight is added and integrated to mature and advance the engineered system. Even when the system is complete, its enormity and complexity belie full comprehension by any one person or group of people. An understanding of the large engineered system will continue to depend on interaction for system understanding.

While much literature focuses on knowledge (whether individual or collective) as a quantity to be stored and transferred, increasingly, there is recognition and a theoretical "perspective that focuses on the 'knowledgeability of action,' that is on knowing (a verb connoting action, doing, practice) rather than knowledge (a noun connoting things, elements, facts, processes, dispositions)."[49] Orlikowski describes the interrelation of knowing and organizational practice as: "competence generation may be seen to be a process of developing people's capacity to enact what we may term 'useful practices' – with usefulness seen to be a necessarily contextual and provisional aspect of organizational activity."[49]

The following two respondents (team leaders with over 30 years experience) describe their teams' interactive practice and the resulting maturation of system understanding:

- *"So if you can integrate all that and bring people together from [element A] perspective, the [element B] perspective, the [element C] perspective, and look at what the common goal is, what the common benefits are, they can start talking about that. 'Well, yeah, we can do that, but you know, if we do that, then we're going*

to have some [challenges here]—I've got a way to solve that. Let's do that this way. If you can compromise here, I can compromise there, then we can get a net win.' I mean it's hard to say these in advance."

- *"Sometimes in working outside your own group, they'll bring in ideas they had that you didn't think of…. [Given a particular existing requirement] you have this idea in your head based on maybe previous experience and [someone outside your area] will come in and say, 'Oh, no. We're doing that different now. This is a much better way to do it.' That can happen."*

As these respondents describe, the initial requirements and thinking that begin R&D are updated through interdisciplinary interactions. Some respondents clarified that the challenge is not meeting the provided requirements, but rather questioning them so as to seek solutions that go beyond them. Two respondents (team leaders with over 25 years experience) explain:

- *"I don't want to simplify it, but whether or not you want to meet the objective or to exceed the objective."*
- *So, I can take those numbers and I can [give] you something that will meet those requirements, but it's only going to meet those requirements because those are the only things I know it needs to do. Now, well, it gives you a solution but is it the best solution? Where we're seeing with the [discipline A] and the [discipline B] people talking to each other now, all of a sudden the [discipline B] people go, 'You've got a [discipline A] that can do that? Oh, well let me change my requirement. I didn't know you could do that. I gave you something I thought you could do.' I think that what I see happening is that it causes everybody to go back and question the requirements and really understand, is this actually a requirement or is this just the way we've always done things?"*

The respondents above portray scenarios in which out-dated assumptions were made regarding the capabilities of a discipline. The ignorance of new technological capabilities in other disciplines is to be expected as technology advancement continues to explode in terms of pace and new opportunities. Cross-discipline teams increasingly must rely on updating their understandings through interaction. For this reason, one single-discipline team leader with over 25 years experience describes focusing on obtaining "directions" for new R&D for a system rather than "requirements" for the system:

"I try to soften words like requirements because I think, in a lot of cases, we hamstring ourselves. 'Well, what do you need? I don't know. What can you give me?' So, I've been trying to push against that and say, 'okay, what's the best you can do today? Let me give you a range and you go and see what you can do with

it. I'll go and see what I can do with it. Then we'll get back together in a couple weeks and [re-visit this topic], if you can make it just a little bit [different here] I've got all these benefits. So, it gives me a direction. All I need is a direction. I don't need an absolute number. I need a direction."

Like many other respondents, this respondent explains that the work of *collaboration* or a *collective* does not suggest that different disciplines are physically working together continually. The experts from the different disciplines convene, interact, then separate for a period to advance R&D and re-convene. The respondent above continues:

"We've so hamstrung ourselves by handing out a number that a lot of times people won't do anything until they know what that number is. So, what I'm trying to do is change that and say, 'okay, you don't need a number. You just need a direction because you aren't going to be able to tell us a number of what your [discipline A] properties are anyway. You've got to do some development. So, all that's important is that we know that this is the direction.' And where does that direction come from? The direction comes from understanding the bigger system. … I think that that cross-fertilization – what it's doing is it's giving direction. Just by meeting every two weeks, everybody in there is getting a little bit of a refinement on the direction on their own work because we're all trying to line up to build the same [system]. So, I think that everybody goes back out, and they work on their own little thing, and they come back in, and they're so energized, and they say, 'Look what I did.' It really is infectious."

Many other respondents also described the positive "infection" of learning through the interdisciplinary interactions. It should be noted that the respondent above took extraordinary efforts to create team cohesion to create a teaming scenario they described as "safe" for acknowledging ignorance. This respondent and, very consistently, others who proactively worked at developing positive interpersonal relations encouraged their teams to be more open to embracing the opportunity of ignorance rather than avoiding the embarrassment of it by building positive social capital in their team interactions.

Chapter 7 Ignorance Becomes Opportunity and Social Capital Becomes Essential

Summary

This chapter summarizes and elaborates topics related to ignorance, learning, and social capital that were interwoven in nearly every aspect of this research effort. Despite the significant challenges with working in an interdisciplinary environment, nearly all respondents described significant learning opportunities that resulted from the interactions. In a sense, the ignorance that is inherent to interdisciplinarity becomes useful. However to effectively exploit the diversity of thought in the interdisciplinary interactions, significant social capabilities are necessary as argument and personality differences are intrinsic to working across disciplines.

Introduction

The preceding discussions in this report have identified several substantial challenges with interdisciplinary interactions in R&D and early design of large-scale engineered systems. I begin this discussion by summarizing some of these challenges noted thus far. From an organization culture view, incentives may not be in place; roles and responsibilities may not be clear or may be confusing; and the underlying organization culture may not be supportive. Prevailing system views or mental models may favor modular system elements and multidisciplinary approaches, thus methods of combining disciplines may favor multidisciplinary juxtaposition. Existing organizational structure and processes may strain needed interactivity and inhibit interdisciplinary cognition; yet, existing social networks may be insufficient to compensate for these constraints. Dispersion of team members further strains interpersonal interactions. Planning is less stepwise and more recursive and iterative in interdisciplinary interactions, making progress difficult to assess by participants and managers and language differences can make communication difficult and time-intensive. In addition,

existing, well-understood system methodologies may be insufficient or counterproductive and existing disciplinary knowledge may be questioned. Ignorance is inevitable (and uncomfortable); and, ambiguities and related confusions are high.

Why work in this environment? Some respondents appeared to revel in it despite these challenges. Interestingly, the ignorance that underlies the interactions was a source of great learning and opportunity for many. A senior researcher with extensive experience in interdisciplinary teams states: "*It can't be codified…. The questions that [different disciplines] ask may be partially out of their ignorance, but that ignorance can also be brilliance because it asks a question.* Another respondent with similar experience replies: "*coming at problems from totally different directions seeing it from a new light can spawn new ideas.*""

Emergence from Ignorance Through Interactive Learning

Klein furthers the discussion on the learning nature of interdisciplinary interaction in this excerpt:

> "Cooperation and interplay… The parties involved learn from each other as they work together. They seek each other out, they become aware of their own limits, and they create a shared sense of a situation through testing individual dilemmas and the assumptions underlying those dilemmas. Maturing and deepening through cooperation and interplay utilizes feedback loops and is reflexive.
> Creativity is embodied in the act of crafting multiple elements into an organic whole. … individuals and groups draw from a repertoire of examples, images, understanding, and actions. The process is necessarily iterative and dynamic, because it starts with partial information. Insight develops through exploration and experimental application of familiar techniques to new situations."[46]

Though the ignorance of interdisciplinarity breeds discomfort as was described by many respondents, many respondents also embraced it as an opportunity for learning and discovery and appeared energized by it. Madhavan states: "the potential for new knowledge is embedded in the team and its interactions."[57] Respondents spoke often of discovering concepts that were not planned. Table 17 provides examples of some comments from five different respondents on the benefit of the emergent nature of the interdisciplinary exchange.

Table 17 Benefits of the Emergent Nature of Learning in Interdisciplinarity from Five Different Respondents, all with Over 25 Years Experience

- *There were a lot of positive things that came out of it that probably were not on anyone's objectives list going into it. I didn't start out with the prime objective of understanding about [X], about [Y]—of [these systems] and [Z] in [those systems]— because I didn't think I needed—I didn't know I didn't know that. I didn't start out with that as an objective. It just comes out of it.*
- *[Without working across disciplines] there are opportunities to share that would get missed. Knowledge would stay locked in, away from each other. Also I think sometimes the results coming out are very narrowly focused. And they answer the question at hand but they don't answer bigger questions. They don't necessarily feed into the next thing. I think when you start getting people connected up they start seeing opportunities and that leads not just to the one thing but to the next thing, new opportunities.*
- *In a productive meeting, you wind up in a different place: design evolves, thinking evolves, and something has changed. In an unproductive meeting, nothing has changed.*
- *It made me think about different ways to approach a problem.*
- *"Because I'm looking at it from a different perspective, I'll say something [to another discipline] that to me seems pretty obvious and they're going, 'I never thought of it that way.' All of a sudden they're going, 'Wow, this has opened up a whole new area of research for me."*

While some respondents expressed concerns that interdisciplinary research might dilute single-discipline research, most argued that, in their experience, interdisciplinary interactions enhanced single-discipline research or potentially helps to advocate for further research: *"For a highly specialized person, the collaboration may give them the perspective needed to justify them continuing in that narrow specialty."*

Respondents also spoke of pressing beyond conceptual designs that initially appeared unwise. Interacting with other disciplines brought about new ideas and technologies that made previously unviable concepts viable. "Ultimately, the domain of interdisciplinarity is the domain of argument."[46] The arguments that were natural in many interdisciplinary interactions were often mitigated by social and intellectual respect and trust, enabling new engineering concepts to emerge. Two respondents with over 25 years experience who lead cross-disciplinary teams explain:

- *"This was a [discipline A] revelation that happened because the [discipline B] and [discipline C] pushed and said, 'Hey, why do you do it that way?' It landed on somebody who was receptive enough to thinking about it differently and going, 'You*

know, what you said is brilliant.' Everybody else just said, oh that's stupid."

- *"Without the contributions of the other people, the possibilities that [the technology] would advance from the [discipline A] side, the possibility of using [element X], which is clearly a dumb idea, you know, up front, it looks like 'why would you do that? That's ridiculous.' That's going to take [inefficient sub-systems] and all sorts of reasons why it doesn't look like a good idea, until you take into account, 'Well, but see, you do this, and you do this.' It takes—you have to knock down several tall poles [in different disciplines] before it makes sense. … We're all learning, and I think everybody enjoys it because it's new and different, and especially because when people first encounter it, they're pretty sure it's not going to work, and understandably. … This ought to come up every now and then in [our] research - that we haven't done [something] before because we didn't have this class of [technologies]. Okay, now we can."*

Social Aspects Underlie Interdisciplinary Interactions

The interdisciplinary interactive arena of R&D and early design for large systems is one where boundaries are not ignored, they are re-evaluated. Disciplinary knowledge is not erased, rather: "The worldview or perspective embedded in each disciplinary piece is extracted, compared, and evaluated for relevance. When conflicts are detected, they are clarified. They do not disappear, however, in a false unity that denies difference (Klein 1995; Klein and Newell 1996)."[46] Many respondents, including managers and leaders, appeared to desire and reward a more unified approach to interdisciplinarity, trying to dampen differences and confusions. The characteristic re-evaluations of roles, procedures, and existing knowledge were difficult for many though they enjoyed the intellectual advantages previously described. Klein writes of this historical interdisciplinary ideal:

> "The older interdisciplinary ideal was a world in which differences were to be overcome. The reality is that differences matter. Even if negotiated and mediated, differences do not go away – they continue to create 'noise.' Misunderstandings, animosities, and competitions cannot be mitigated or glossed over. They must be taken seriously as attempts are made to spell out differences and their possible consequences. Interdisciplinarity conceived as communicative action does not trust that everything will work out if everyone will just sit down and talk to each other. Decades of scuttled projects and program belie the naïve faith that status hierarchies and hidden agendas will not interfere or that the individual with the greatest clout or loudest voice will not attempt to dominate."[46]

Klein's discussion highlights the inherently organizational, social, and cognitive nature of interdisciplinarity. Respondents were profuse in their comments regarding the social and interpersonal needs of interdisciplinarity in their organization. *Every* respondent noted that interpersonal aspects were central to working with other disciplines. Their descriptions of interpersonal topics were woven through all of the interviews. Ethnographic observations confirmed this. And literature on collective mind and interdisciplinarity also asserts the significance of ongoing positive interpersonal relations.

In conceptualizing the collective mind, Weick notes there is "little room for heroic, autonomous individuals. A well-developed organization mind, capable of reliable performance is thoroughly social. It is built of ongoing interrelating and dense interrelations. Thus, interpersonal skills are not a luxury in high-reliability systems. They are a necessity."[4] In describing collective capability in distributed organizing, Orlikowski describes "knowing is an ongoing social accomplishment, constituted and reconstituted in everyday practice."[49] In researching "creative collectives" Hargadon and Bechky describe "mindful interactions across individuals" to provide for "a collective mechanism for generating solutions."[51] Literature on interdisciplinarity is also consistent in stressing the criticality of social interactions.[6, 12, 14, 17, 46]

From the empirical data from this study, respondents provide their views on the interpersonal aspects of working across disciplines in Table 18.

Table 18 Three Respondents' Views on the Importance of Interpersonal Aspects

Single-discipline researcher:
- *"It's interesting. It's people. I mean, it's people. … You recognize, okay, we're in different planes here, because we're in different worlds. But you also have just the normal" personality thing, where some people—again, we're all professional. ... It's just like there's some people that you can talk real easy to, and there's some people that you just never really feel like you quite connected with, whatever it was they were trying to tell you.*

Cross-disciplinary team leader:
- *"Know how to pull people together …respecting the other individual, listening is a huge part of it. Validating what you hear, making sure you hear it right, sometimes that's repeating it. … I know some of them are very vocal. They're not shy at all. They're very strong-willed, very driven. I think, 'Do I really want to do this?' I've found actually, I liked some of those guys because they're honest and direct with me. I say, 'As long as we come together and talk, we can figure out where we need to go. If I don't know what you're thinking, I don't know how to help and get us where we need to go. If you're stabbing me behind the back, it's counter-productive. I'd rather you just tell me what you think. Be honest, be respectful, but be honest.'"*

MDO researcher:
- *"It's very inter personal so you need to have somebody to be effective—there are certainly ineffective people and you end up with bad meetings. …You can have the best software tool in the world; it doesn't matter. I think it's a training thing. I think it's an inter-personal thing."*

Interestingly, as much as the respondents were passionate about advancing the engineered systems, every respondent consistently noted that interpersonal interactions could enhance or degrade cross-disciplinary interaction. A respondent with 35 years experience notes: *"If you want to produce collaboration, don't give people the idea that they are subordinates."* Table 19 provides other examples of quotes from respondents on the potentially destructive nature of poor interpersonal relations.

Table 19 Examples of the Negatives Impacts of Poor Interpersonal Relations From Four Respondents, all with over 25 Years Experience

- *"It's a personal thing, I think. You find individuals in other disciplines that are more open and things work great. Some people in other disciplines you can push and push and try and try and it never happens."*

- *"What really hurts collaboration, I think, is somebody that wants to dominate the conversation, to the point that other people just go, "I don't need this." The person doesn't probably even recognize it maybe."*

- *"In a collaborative engagement … [an initial] dance where you're trying to figure out what are they saying to me, where do I fit into this, how can I help or what can I get out of the other person—maybe that's, in some ways, speaking to this learning component sort of relationship-wise coming up to speed. It's pretty easy to figure out who the strong personalities are. The whole social engineering part of it; who's worth listening to, who's not, who's going to go off and pontificate and sort of rule the meeting or subsequent meetings? There's the whole personality part of the learning, as well as the technical side."*

- *"If you have a person that's an expert but they have poor interpersonal skills. They are not approachable, but they have the information you need, you have to decide if you want to come and interact with them and deal with all of the other stuff that comes with the information that you're seeking, and that you need to solve [your engineering problem]."*

Familiarity with other team members is an important aspect of making the cross-disciplinary effort work effectively. As the teams grow larger and become more geographically dispersed, developing social familiarity becomes increasing challenging. Respondents spoke of spending time outside of formal meetings to build relations. Examples from three single-discipline researchers follow:

- *"Strongest relationship always has some social component to it, go out after the meeting at the conference. [Or]..Reminisce for 10 min."*

- *"A lot of times you know I feel like: 'I don't know you, and therefore I don't want to talk to you.' A lot of it is just getting to know somebody. Once you pass that, 'somebody you can break the ice with,' it's not so frightening frankly."*

- *"If you've got two groups that have worked together previously and there are some connections and some familiarity amongst the participants, it's fairly easy to form a group again. When you've got groups that haven't worked together before, it's a lot more-- sensitive, I guess, for lack of a better word. There's both, that shared vocabulary that hasn't been developed. You lack that and you also, in addition, lack the personal piece: the 'I've never met you before, and so I'm going to be a little more reserved than I usually am' and perhaps not say as much. There's a piece that is personal as well as technical."*

The significantly influential role of high quality connections (HQC) and positive social capital in organizations has been described by Dutton and Baker.[54, 55, 67, 68] HQCs are interpersonal connections that can be momentary and short term (not necessarily a deep relationship between the individuals) but "can have a profound impact on both individuals and entire organizations."[67, 68] Essential ingredients of HQCs are "mutual positive regard, trust, and active engagement on both sides."[68] The empirical data of this study adds to the literature in identifying several crucial challenges that inter-organizational personal connections and positive social capital must mediate in working across disciplines in R&D and early design of large engineered systems. Below I identify four prevailing areas of individual discomfort that are intrinsic to the working environment of the study topic, and the opportunity that can be created through building positive social capital:

1) The discomfort of ignorance, and the creation of a safe place for open discussion.

2) The discomfort of unfamiliarity that is inherent with dispersed team members, and the creation of opportunities for informal interactions.

3) The discomfort of confusion in communicating when different disciplinary languages are being spoken, and the facilitation of common understanding.

4) The discomfort of an unspecifiable future endpoint due to the recursive and emergent nature of interdisciplinarity, and the creation of socially and technically respected success metrics in an on-going system evolution with ad hoc social connections.

In this study, many respondents described the discomforts above and the importance of leaders who could mitigate them. The leaders typically were not supervisory line managers or program managers, but rather were senior researchers with exceptional interpersonal skills who worked at a level lower than line managers or program managers. All respondents were unequivocal in stating there were specific individuals in their organizations who were exceptional at facilitating interdisciplinary interactions:

- *"Some people are good facilitators without necessarily being aware of it."*
- *"There are some people who are good at seeing connections, who are good at seeing how working together is going to benefit the group and then also conveying*

that to people. … There are people who are good at seeing it, but lack the people skills to bring the group on board."

The last respondent above points toward a common misconception in the management and leadership, where those with the cognitive ability and professional training to understand system-level trades were assumed to be the focal point for cross-disciplinary interactions in their organizations, though this individual may not have the social skills to facilitate and sustain the interpersonal interactions. Hence, both cross-discipline and social competence is required for enabling cross-disciplinary interactions. An MDO/MDAO researcher describes his or her perspective:

> *"I think the most important part of MDAO is really the interpersonal part. I think we've—as a discipline—because I consider myself an MDAO researcher—I think we've got a handle on or we're moving toward getting a handle on the technical aspects of it. I mean there's always more research to be done but we understand very well about systems and optimization and configuration and things like that. Computational costs still a challenge but we're working on it. But we haven't really started to address the inter-personal issues. I think that's the most important."*

Respondents also explained that the organizational structure of cross-disciplinarity runs orthogonal to but not against the existing hierarchy. Disciplines interacted across buildings, line organizations, programs, and geographic regions via ad hoc personal connections throughout their large organizations in addition to working within formally structured cross-discipline teams. In Figure 10 one respondent describes an expanding and informal network that they hope to enable through working across disciplines.

> *"Right now the 'between discipline' interaction has been much more personal connections, much more ad hoc, out of necessity. I need to [X]. So, tell me who out here [does that]. So, the [two] come together, not necessarily going through the MDAO person [or an official manager]. It's who do you know. It's that personal network in a lot of cases, I think. So, part of what I've done is build a personal network where everybody is introduced to each other. So, in forming this group, now we've got this personal network and my hope is that each one of these people goes back into their home organization, their stovepipe, but if somebody else says 'hey, I need an [X]'—and I've seen this happen. I got an [X] question. It's like, 'oh, well here's my [X] contact. So, all of a sudden now somebody else in one stovepipe is calling this [X] contact in another stovepipe*

> *because of that personal connection. So, it doesn't go through the MDAO folks [or management] at all. After there gets to be a relationship and a trust that seems to happen more ad hoc. So, instead of having a centralized network, it becomes a distributed network where those connections happen discipline to discipline through the people that they know. So, each of those people almost becomes a node on the map. So they've got all these other [X] people, and this has all these other [Y] people, and this has all these other [Z] people. So, this guy comes to here and he says, 'Oh, go talk to him.' Then he says, 'Oh, go talk to him,' as opposed to coming back up through the center."*

Figure 10 Vignette from a Senior Researcher and Cross-Disciplinary Team Leader with 27 years experience on Creating a Network to Facilitate Interdisciplinary Interactions

Brief Look at Individuals that Foster Interdisciplinary Interactions

I close this discussion with a look at some of the traits of individuals who foster interdisciplinarity, as identified by many of the respondents. While the individual level of analysis is beyond the scope of this study, a few aspects of this study conspicuously pointed to individual constructs. I highlight a few salient observations at the individual level due to their consistency in the data and their confirmation in the literature.

The data gathered showed that respondents who spoke most extensively about *collaborative* and mostly *collective* interactions and thus have a more complex systems view exhibited a few consistent traits that distinguished them from most of their peers. These respondents were consistently very cognizant of the need to build interrelations. They proactively took steps they described as unconventional to build the relationships among disciplines, including setting up rooms for co-location and taking advantage of business trips to facilitate team cohesion.

The individuals were also emphatic about the proximity of some of their teams' interactions even if they occurred infrequently. For example, these respondents metaphorically use phrases of close-knit interactions to describe how they would like their teams to interact such as: *"you will sit in this room and you will talk," "iron cage match," "[re-locate and] work within our group," "No! [regarding separate efforts united by a common goal] … I've asked them to get together—to come together collectively and tell me [what the challenges are]."*

Each of these respondents also exhibited strong narrative skills and used colorful story-telling to convey their thoughts to me as well as their peers and team members.

The literature on collective mind supports this observation: "narrative skills (Bruner, 1986; Weick and Browning, 1986; Orr, 1990) are important for collective mind because stories organize know-how, tacit knowledge, nuance, sequence, multiple causation, means-end relations, and consequences into a memorable plot."[4]

Regarding their diverse team members, each of these unique respondents had a deep belief in, and sincere admiration of, the different disciplinary abilities of their team members. Their personal respect for their team members was palpable. Further, each of these respondents proactively sought to make unconventional and unusual connections between disciplines. And, each was driven by a passion to discover potential breakthroughs and explore new risky research territories, though each admitted (and yet was somewhat tenaciously undeterred by) the low odds of actually making a disruptive breakthrough in these areas.

These respondents exhibited many of the characteristics described in other literature as: 1) the "connectors, mavens, and salesmen" described by Gladwell;[122] 2) the "energizers" described in POS literature by Baker;[54, 64] and 3) the highly desired "deep generalists" described by McMasters.[123, 124] All of these respondents were well respected by their colleagues, had a vast social network, and were often sought out by their peers and management for highly cross-discipline efforts.

Chapter 8 Contributions, Implications, and Propositions

Summary of Findings

In this descriptive analysis, I identified several aspects of organization culture that relate to interdisciplinary interactions. In general, the organization culture did not support interdisciplinarity very well due to lack of clear roles for leading it, incentives to encourage it, and a structure that is insufficiently flexible to encourage it. Yet, a sub-culture exists that values interdisciplinary interactions and the design-orientated perspective it employs. In fact, several respondents and their respective teams were found to particularly revel in interdisciplinary interactions, enjoying the intellectual discovery that is foundational to such interactions.

The means and motivations for interdisciplinary interactions in R&D and early design of LaCES cannot be easily generalized for they are not focused solely on hardware integration, large software integration tools, or interface control documents. Rather, a wide variety of means and motivations were discovered. Some of these include sharing resources, such as a project team *coordinating* financial resources to increase efficiency. In other cases, several researchers would aid a single-discipline team to advance their discipline or one particular technology. Some respondents were merely helping a colleague or friend in another area. However, most frequently, truly interdisciplinary interactions were driven towards solving, creating, exploring, understanding, or designing aspects that did not fit neatly within one discipline. Hence, problems were solved, new capabilities were created, an idea or new phenomenon was explored, between-discipline concepts were understood, or a new system or technology was designed.

Underlying all of these example motivations is the system paradigm that one holds. In this study, two primary paradigms of engineered systems were identified. One paradigm views the system as more of the deterministic result of combining mostly modular elements in a hierarchical decomposition. This more modular view tends to favor multidisciplinary interactions over interdisciplinary interactions and focuses on

understanding elements over their interactions in the system. Another paradigm views the system as a nondeterministic result of combining highly intertwined elements that may be best described as networked in the system. This latter paradigm is a more complex view that tends to favor interdisciplinary interactions over multidisciplinary interactions and understands system elements by understanding their interactions in the system. The more complex view assumes ambiguous and emergent behaviors in the system are inherent and that all aspects of the system cannot be fully predicted. The other more modular view assumes ambiguity and emergence may be sufficiently addressed or eliminated with additional understanding. The two paradigms underlie the primary perspectives on interdisciplinary interactions found in this study.

Four primary means of combining disciplines were also identified in this study. These were described in a sensemaking framework that encompassed the following: *connecting*, *coordinating*, *collaborating*, and a *collective*. The interactive needs of these different methods vary considerably. However, these differences are often not appreciated, resulting in frustrations and confusions from differing assumptions within researchers and managers. For example, the commencement of interdisciplinary interactions, their frequency, expectations of engagement, and clarity of system definition are very different for the four methods. The four methods also relate to cognitive frameworks respondents use to understand different systems. Those with a more modular system view used more *connections* and *coordinations* and those with a more complex system view used more *collaborations* and *collectives*.

Structure was identified as a key influencing factor in the interactions between disciplines. That structure could be the organization of people or the architecture of the engineered system. Very often, boundaries of action and thought are created by the structure used, constraining and influencing engineering outcomes. Pressing beyond these boundaries often involves working outside traditional hierarchical organizational and engineering processes. Interdisciplinary interactions are sensitive to the initial conditions that derive from organization or program structure, the engineered system architecture or configuration assumed, and the manner in which the engineering problem is formulated such as: 'design a system,' 'create a capability,' or 'connect hardware or software.'

An important aspect of the findings is the significant influence of social capital on interdisciplinary interactions. Simply, positive social interrelations encouraged interdisciplinarity and negative interrelations discouraged it – regardless of the engineering need or management direction. Positive social interrelations are pivotal for addressing some of the negative emotional arousal associated with interdisciplinary interactions in large, dispersed engineering organizations. Negative emotional arousal stems from a variety of sources including: ignorance; confusion; new people; new organization and related culture; potential career impacts; and, ego. Ignorance resulted from a lack of understanding of other disciplines. Confusion resulted from unfamiliar processes and ambiguity. New people, organizations, and culture created discomfort and considerable mitigated speech and slowed action. A single-discipline focused incentive system often resulted in respondents being concerned about the potential career impacts of working across disciplines and, all of these challenges impact ego.

Mitigating these challenges requires continual attention to building positive social capital. The tenets of social capital [54, 55, 64] coincide well with what respondents described as needed elements of interacting across disciplines. Their comments centered on the need for respectful engagement and valuing people's contribution to the interdisciplinary interaction. Respondents also described a need for trust – both intellectual and social trust. Intellectually, respondents wanted their ideas to be heard and their ignorance not to be a source of embarrassment. Socially, respondents wanted to be welcomed and valued as colleagues or friends.

A need for generalized reciprocity was also clear and consistent. When interdisciplinarity tended toward a one-way exchange, respondents were reluctant to engage fully and were often dissatisfied with the interaction. Reciprocity and joviality are inherent in the most effective interdisciplinary interactions. All of these aspects – respect, trust, reciprocity, and joviality – are also key tenets of positive social capital.[67, 68] The literature on positive social capital also notes that there are significant, organization-wide benefits to building positive social capital that improve interdisciplinary interactions as well the broader organization. These include: broader thinking, better learning, enhanced cooperation, greater attachment of employees, increased job satisfaction, and other benefits.[67, 68]

While culture, structure, methods, paradigms, and social relations are significant aspects of interdisciplinary interactions in R&D and early design of LaCES, the heart of the interactions may best be described as intellectual transformation. Thinking, understanding, awareness, and knowledge evolve in the interactions. While some respondents had a concern about the dilution of single disciplinary research as a result of interdisciplinary research, a more complementary and interdependent relationship between single discipline and interdisciplinarity was observed. Discipline understanding is foundational for interdisciplinarity. And interdisciplinarity enriches single disciplinarity by spawning new ideas, updating thinking, increasing system relevance, and exploiting new single discipline findings. While the two approaches may be accomplished in absence of the each other, the richness, effectiveness, and efficiency of both single disciplinary and interdisciplinary research is greatly improved when the two work in concert.

Particularly for LaCES design, disciplinary depth is requisite for understanding complicated phenomena and interdisciplinary understanding is requisite for addressing the interdependencies that are intrinsic to the system. In short, LaCES cannot be understood nor effectively designed without both single discipline depth and interdisciplinary breadth. However, this is not an argument that may be simplified to a need for specialists and generalists. Rather, the data clearly indicate that interdisciplinarity is practiced in a wide range of time investment from only 5% of a respondent's effort to 95% of his or her effort with this effort varying as needed for different projects. For example, some respondents would spend a year or two in a focused single-discipline area and then a year or two applying their single discipline knowledge to a specific cross-disciplinary task and then return to single discipline research again, etc. However, most respondents vacillated back and forth from single disciplinary to cross-disciplinary efforts on a more regular basis.

Another aspect of interdisciplinary intellectual transformation that is particularly relevant for LaCES is the discovery of the unknown between conventional knowledge domains, mathematical models, system elements, organizational structures, etc. The unknowns may be new technological capabilities or potentially dangerous couplings that may only be discovered through interdisciplinary interactions. For complex systems,

often problems and opportunities do not arise where you are looking but rather where you are not looking.[125] More comprehensive system knowledge is interactively constructed through the interdisciplinary discussions that include both debate and affirmation. Opportunities for creativity are created and greater awareness of system interdependencies is increased.

Integrative Theoretical Framework

In summary, the interdisciplinary interactions during R&D and early design of LaCES may be represented by an integrative framework that captures three synergistic key elements: the engineered system, the people working on the system, and the methods they use to work on the system. Or alternatively stated: 1) what is being worked on or the product under development (e.g., an aircraft or integrated technology); 2) who is doing it or the people involved (e.g., a large dispersed organization or team); and 3) how they are doing it or the processes being used (e.g., MDO, promotion process, design reviews, face-to-face communications). For each of these elements, the considerations are multifaceted. In considering the product, the size, complexity, and structure are important aspects of interdisciplinary interactions. In considering the organization of people, the dispersion, size, culture and structure of the organization are influential. And, in considering the processes underway, not only engineering processes are important, but also organizational, and social processes are significant. Figure 11 captures the integrative theoretical framework that was created as a part of this work to summarize these findings.
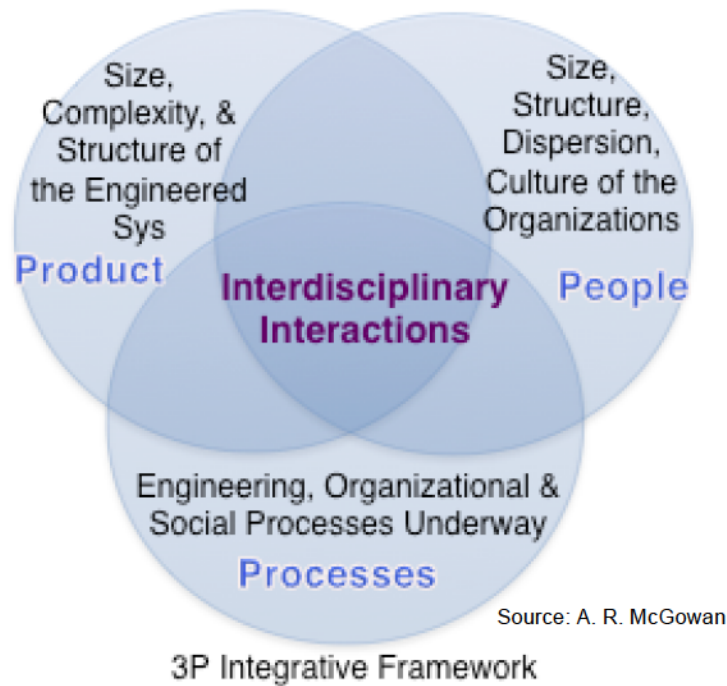
Source: A. R. McGowan

3P Integrative Framework

Figure 11 Integrative Theoretical Framework

This framework graphically depicts the very strong couplings between the organization, the processes used, and the engineered system. Many processes used were not driven by the needs of the engineered system but by innumerable other factors including incentives, organization structure, and a person's own social network. In a similar vein, regardless of the detail of the engineering requirements, different organizations and people can yield very different solutions.

Cross-disciplinary interactions are likely a function of other aspects not captured in this framework. This raises the unanswered question of: What other circles should be included in the framework? The above framework may serve as a starting point for dialectic discussions to address this and other questions regarding interdependencies in working across disciplines during R&D and early design.

Dissertation Contributions

The dissertation contributions are as follows:

1) A unique data set that did not focus on using a sample of university students, an artificial laboratory setting, or a simulation – an often common approach in the literature. Rather I obtained rich, descriptive accounts of current engineering practices and related perspectives from experienced practitioners within large, geographically-dispersed engineering organizations that develop large-scale complex engineered systems.

2) A rigorous data analysis using a triangulation approach of open-ended surveys, semi-structured interviews, and ethnography, augmented by member checking and peer review from scholars in organization science, psychology, and engineering.

3) An interdisciplinary research approach integrating theories from engineering, organizational sensemaking, positive organizational scholarship, and interdisciplinarity, fusing of these genres of literature with empirical data of actual engineering practice.

4) A rigorous, interdisciplinary understanding of work practices in engineering resulting from the above synthesized data analysis. The findings reveal key aspects of organization culture, structure and processes that influence interdisciplinary interactions.

The analysis delineates principal characteristics of the primary engineering practices used to work across disciplines and the implications of such practices. This research discovered many implicit assumptions regarding work practices, the analysis of which can provide important insights for both leaders and practitioners. This work also elucidates many specific problem areas and areas of opportunity, providing directions for further improvements to engineering practice and research. Ultimately, the improved comprehension of work practices and perspectives on interdisciplinary interactions provided can provide a rubric that organizations can use to reduce confusions and improve efficiencies.

Implications and Propositions

This research effort identified several important challenges as well as benefits to working across disciplines. The challenges are costly as they include considering incentives, organization structure, roles and responsibilities, proximity of employees, interrelationships, and many others. The benefits are significant as they include mitigating risks, enhanced creativity, greater system understanding, and others. Nonetheless, interdisciplinary interactions are likely not needed for all aspects of R&D and early design of LaCES and they may best be implemented in varying degrees depending on the system and the organization. In this section, I explore three areas in brief: implications, propositions, and future work. In discussing implications, I focus on a comparative analysis of common misconceptions regarding cross-disciplinary work practices in R&D. In exploring propositions, I focus the discussion on potential steps to foster interdisciplinary interactions in scenarios that may benefit the most from these interactions.

Implications: Refuting Assumptions of Practice with Findings from Actual Practice

While it is common to refute theory with data from practice, this study led to findings about engineering practice that refute some assumptions about practice. In Table 20 I provide a high-level contrastive summary of some common assumptions about engineering practice compared to findings about actual practice. It is important to note that this table is neither exhaustive nor exclusive and the common assumptions about engineering practice listed are valid in innumerable scenarios yet were not valid in many of the interdisciplinary scenarios studied. This table is presented not to suggest that common assumptions of engineering practice are incorrect but rather to identify where the findings of this study suggest that some of these assumptions may need to be updated or augmented.

Table 20 A Comparative Analysis of Assumptions About Practice vs. Actual Practice

Common Assumption Regarding Interdisciplinary Interactions (II) in R&D Practice	Study Findings Interdisciplinary Interactions (II)
A Well Defined Set of Requirements, Articulated Upfront, Is Best Practice Or: The Key Parameters/Requirements for the System of Interest Should Be Known and Clearly Articulated Upfront	The Real System Requirements Are Not Known (and Can't be Known) in Detail Upfront – They Are (Necessarily) Co-Constructed Throughout the R&D and Early Design Process. Thus: • The benefits of II can't be predicted a priori and some II will not lead to a useful solution • The system objective function is often changed during II • The requirements can overly constrain II and may not result in the best solution.
Viewed at a High Level, II in R&D and Early Design is a Convergent Process Advancing Toward A Closed Design of Sub-Systems or Whole Systems	The process is often divergent and emergent leading to new understanding and design concepts. Learning, Debate, and Creativity, are Inherent to the process.
MDO is the Primary Integrator of Disciplines Throughout the R&D and Early Design	Relationships and key people with multifaceted skills are the primary integrators
The Impediments and Enablers to Effective II are Largely Technical, Relating to Math Models, Software, and Hardware. Thus, Integration is driven by and best facilitated through the integration of math models, software, and hardware, and documentation of these aspects.	Social, Organizational, and Cognitive Aspects are the key impediments and enablers. Integration is best facilitated through social means such as relationships, proximity, teaming, and communication. Math models, software, and hardware are critical elements of integration. However, in some cases what is to be integrated is knowledge to foster new understandings.
Managing interfaces can be done via handling transactions of data via detailed documentation such as interface controlled documents (ICDs) and configuration control documents	Interfaces must be documented and they may be controlled but another description is that the interface must be discovered and understood through an iterative discussion between experts from the relevant fields. Very possible that there is a lack of awareness of some aspects of the interface.
Uncertainty or lack of sufficient information is the primary engineering need	Ambiguity or lack of sufficient understanding and awareness of unknown issues may be as important.
An Incentive System Focused Toward High Technical Competence is Best Practice	• An incentive system focused toward high technical competence can drive people toward focusing on individual sovereignty over system best. • Ignorance should be embraced and used to trigger more research • High social competence is also needed.
Ignorance is Unacceptable	Ignorance is inherent to the process and may be useful.
Organization Structure Does not Significantly Impact the Technical Solution	Organizational Structure iplays an influencing role on engineering outcomes
Experienced, Technically Competent Engineers are Willing To Work Together to Enable the Best Technical Solution	Egos, Existing relationships, Career Aspirations and protection, Incentives Systems can greatly influence actual interconnectivity

Examining Table 20 suggests that an improved awareness of engineering practice can update our assumptions and potentially enhance work practices and engineering outcomes. For example, perhaps designing organization structures to better suit engineering needs may lead to avoiding some of the challenges noted in this document. Or, perhaps ignorance can be encouraged to be used as a trigger for further investigation rather than a source of embarrassment. Subsequently I explore several propositions for fostering improved interdisciplinary interactions in R&D and early design of LaCES.

Propositions: Fostering Interdisciplinary Interactions in R&D and Early Design of LaCES

Existing theory and the findings from this study indicate that interdisciplinary interactions are most beneficial to certain engineered systems and organizations. The subsequent summary is not exhaustive, but represents principal characteristics of engineered systems and the related R&D organizations that might benefit the most from interdisciplinary interactions. These include the following types of engineered systems:

- Systems with many ambiguities, where significant aspects of the engineered system cannot be fully predicted, can benefit from the intellectual discovery of interdisciplinary interactions.
- Systems with many interdependencies, that may include engineering and socio-technical interdependencies, can benefit from a focus on interactions over elements.
- Systems requiring collective or distributed cognition to fully comprehend the system will certainly require interdisciplinarity as the system is not comprehensively knowable by any one group.
- Systems with multiple organizational entities (internal and/or external) can benefit from the various skills of interdisciplinarity where inter-organizational challenges are similar to interdisciplinary challenges.
- Systems that connect to or are interdependent with other engineering or non-engineering systems will inherently require interdisciplinary interactions to facilitate innumerable connections. The other systems may be very diverse such as: another

LaCES; culture or processes of a major sub-contractor; or local infrastructure systems such as the local transportation system, nearby educational institutions, or tourism in the area.

For the above scenarios, interdisciplinary interactions may be crucial for enabling effective and efficient R&D and early design. In these scenarios, both the organization and the engineered system are at extremes, with considerable dynamics and complexity, where theories from the literature on Positive Organizational Scholarship (POS), High Reliability Organizations (HRO), and sensemaking may be particularly beneficial. The implications below will focus on scenarios where interdisciplinary interactions are of most use.

Sensemaking theory and HRO research focus less on perfecting known standard operating procedures (SOP) and more on responding well when things do not go as planned. While standard operating procedures exist and are necessary, they are recognized as insufficient for many organizational operations since "knowledge is incomplete, information is imperfect, and analysis is fallible."[126] For LaCES organizations this means making ignorance useable by allowing it to trigger sensemaking, question asking, debate, inquiry, and additional research. This means embracing the opportunities brought about by ignorance and doubt.[77, 78, 126, 127] The current prevailing culture of rewarding depth of competence is good yet incomplete for addressing engineering and non-engineering dynamics, unknowns, and interdependencies. In one study, Macrae describes how "investigators assumed that some set of risks would always lie beyond the limits of their awareness."[126] These investigators worked with the tension of assuming the inevitability of ignorance while having intolerance for it – when they were in doubt or reached the limits of their awareness, they responded by initiating further in-depth study. Some of the most significant challenges (and perhaps opportunities) of LaCES design may lie between what is already known and just beyond current awareness.

Addressing the unknowns and other on-going dynamics of LaCES development also requires a focus on organizing, improvising, and updating our thinking, planning, managing, and leading on a nearly continual basis. These tenets of dynamically organizing to address the varying and changing needs of the organization are noted in

several studies in sensemaking.[70, 73, 76, 80, 108, 126] Roe and Schulman report that "reliability is not the outcome of organizational invariance, but, quite the contrary, results from a continuous management of fluctuations both in job performance and in overall departmental interaction. It is the containment of these fluctuations, rather than their elimination, that promotes overall reliability."[78] In POS, the competing values framework highlights the simultaneous existence of different competing values within an organization requiring adjusting between different types of organizing.[128] In contrast, the data in the current study points toward a tendency for stable processes, fixed organizations, and little changes to plans. However, working across disciplines requires adaptability and improvisation.

Another challenge faced in interdisciplinary interactions in LaCES R&D and early design is that many cannot "see" how their work fits into the overall system. Confusion or misunderstandings about what is important from other disciplines is common. Very often one discipline oversimplifies the impacts of other disciplines. An assumption that the system technologies, configuration, and disciplines are lightly coupled or are very lightly interdependent is frequent at the beginning of many cross-disciplinary exchanges. Simplifying assumptions gave rise to a great deal of the argument in interdisciplinary interactions. However, as noted earlier, the argument and discussion are invaluable as knowledge and understanding is enhanced. It is clear that clarifying the interdisciplinary connections, impacts, and assumptions is essential to improving R&D and early design of LaCES as this enables the benefits of knowledge integration and transformation. Delaying addressing these challenges until after R&D is complete is much more costly. During R&D, interdependencies can be understood then exploited or mitigated. When exploited, new, sometimes disruptive, technologies and system capabilities can arise. When mitigated, costly rework is avoided.

MDO, systems analysis, and systems engineering research and processes are critical to the cross-disciplinary needs of many organizations. And, it is important to note that interdisciplinary interactions in R&D and early design are augmentative but different from these necessary cross-discipline research and processes. This study shows that these processes by themselves are not sufficient to address many interdisciplinary issues, principal ones being social, organizational, and intellectual

transformation aspects.

The social needs of interdisciplinary interactions are also significant. As noted earlier, the principles of building positive social capital can greatly improve the interactions and add important benefits to the rest of the organization. Socially, interrelations between disparate personalities, teams, and cultures must be addressed to foster interdisciplinary interactions. And, "interrelations are not given but are constructed and reconstructed continually by individuals through ongoing activities."[4] Thus, addressing some of the social challenges noted throughout this document will require individuals (in addition to existing processes) who are regularly engaged in making interdisciplinary interactions work by reducing confusion, translating terminology, facilitating knowledge transfer and collective learning, building relationships, enabling interactive activities, and crafting welcoming local cultures. High-level managers or team leaders with other significant day-to-day operational responsibilities may accomplish this to a degree. However those "closer to the ground" may more aptly or efficiently be able to address these challenges more frequently.

Organizationally, interrelations between disparate internal and external organizations, incentives, and processes must be addressed. Networking across hierarchical organizations to proactively and continually create and facilitate dynamic and iterative communication pathways and build positive relationships where necessary is inherently a part of interdisciplinary interactions. This networking will occur in a non-hierarchical, horizontal manner across organizational partitions and including various levels in the organization as needed. As noted in the literature on networks in organizations, particular people have skills that lend themselves toward facilitating these connections well. Other literature refers to organizational roles with some of the related skills, such as: 1) the "connectors, mavens, and salesmen" described by Gladwell;[122] 2) the "energizers" described in POS literature by Baker;[54, 64] and 3) the highly desired "deep generalists" described by McMasters.[123, 124] However, enabling these type of skills to be effectively used will require both strategic job design by managers and job crafting by employees rather than having universal job titles and roles for all staff engineers.[129]

Intellectually, knowledge must be integrated and advanced by weaving together,

rather than "gluing" together, deep knowledge bases. Here, tacit knowledge should be considered in addition to explicit knowledge and knowledge should be constructed socially and collectively in addition to constructing system models numerically and additively. To facilitate this horizontal weaving across different line organizations, narrative and story-telling skills and social awareness skills are needed in addition to documentation, organization, and engineering skills. And for distributed or collective cognition, mindful or heedful interrelating is key. Several research articles detail some of the needs of this type of cognition.[3, 12, 49, 70, 80, 127]

Perhaps the most significant blind spot for interdisciplinary interactions in R&D and early design in LaCES is the assumption by many engineers that combining the output of knowledge is equivalent to combining knowledge itself. Engineering training facilitates adeptness in combining the outputs of engineering knowledge such as software, hardware, mathematical models, etc. However the knowledge integration of interdisciplinarity is a different and augmentative task that often precedes the more mechanical integration of knowledge outputs. To enable knowledge integration and intellectual transformation, a reciprocal and mutual sharing of ideas, assumptions, experience, etc., is needed to co-construct new knowledge, understanding, and awareness. This work is untidy as well as deeply meaningful to the engineers and the future systems they help create as it embodies a creative and exploratory learning activity that can lead to discoveries that lie between traditional competencies.

While challenges of interdisciplinary interactions appear daunting, this study showed that there are those (a few) that do this well. For the future of LaCES design, proactively nurturing multifaceted skills that address complex interrelations that are engineering, as well as social, organizational, and cognitive can be highly beneficial.

Future Directions

Future research directions include other in-depth studies focused on implementing some of the suggested propositions or challenges. For example, while HRO research has been investigated for use in operating LaCES, applying the related theories to engineering R&D and early design practices requires further examination. Also, making ignorance useful requires further study to identify needed cultural

changes, incentive system changes, and changes to work practices. While research indicates that error can be effectively used to create new ideas and breakthroughs[130] and this study identified examples of using ignorance in a similar vein, marrying the theories of creativity regarding error and ignorance with the findings on discomfort in failure and ignorance may provide useful insights on how to enable error and ignorance to be used more effectively.

A significant area of research for working across disciplines in LaCES R&D and early design is in distributed and collective cognition. While the findings of this study identify that these types of cognition are taking place, further study to identify how to practice distributed and collective cognition more effectively may offer important benefits to LaCES engineering and design. Similarly, social constructs were pervasive in this study. Further study delving into implementation of building of positive social capital and building effective social networks in the organization to facilitate improved engineering outcomes across disciplines may have significant benefits.

The ultimate goal of this study is to improve understanding of current engineering practice so as to lay the groundwork for more accurately identifying improvements to practice. It is hoped that these findings enable increased comprehension of interdisciplinary interactions in R&D and early design such that the science of designing large-scale complex engineered systems may be improved.

APPENDICES

Appendix 1 Survey Instrument

NSF/NASA Workshop   February 8, 2012

Please consider your first-hand experiences with research in large-scale, complex engineering systems…

1. How important do you think interdisciplinary interactions are for complex systems?

2. Please describe the potential benefits to interdisciplinary interactions.

3. Please describe the potential negatives to interdisciplinary interactions.

4. Please describe things that encourage interdisciplinary interactions.

5. Please describe the obstacles to interdisciplinary interactions.

6. Please provide some background context for your experience:

   - Where do you work?

   - What do you do for your occupation?

   - How many years of work experience do you have?

7. Please add any other comments you wish below:

Appendix 2 Interview Protocol

Background about recording and consent

- Thank you for taking the time to talk to me. I'll give you some background information to tell you how this interview will work. Feel free to stop me at any time to ask questions. I'll repeat some of the information I sent in the e-mail just to be sure you have all of the information you might be interested in.
- First of all, as I noted in the e-mail, I'd like to audio record your responses to my questions so that I can focus on listening to you and not trying to write everything down, which would likely mean that I would miss something you said.
- Everything you tell me will be completely confidential. To make it confidential, I'll be taking several steps. I will be keeping the recording and the transcription of the recording in a secured location. After the recording has been transcribed, the audio recording will be destroyed. And, any identifying information that connects you to the recording will be removed from the transcription. This also includes removing some else's name that you might mention during the interview. For example, if you tell me that you spoke with Bob Smith, I will remove Bob Smith's name from the written transcription. Again, all audio recordings will be destroyed once the transcription is complete and we've removed all identifying information.
- If at any time you'd like me to turn off the recorder, or it makes you uncomfortable in any way, please just let me know, and I'll be glad to turn it off. No problem.
- Also, I have formally completed a review and approval from the University of Michigan and NASA to conduct this study, which of course uses human subjects, like you. Thanks for helping me with the study.
- As a part of the approval process, I need to get verbal consent from you in order to record you during this interview. Are you OK with audio recording? Thank you.

2 min.

Study Background

- I am currently working on a doctorate at the University of Michigan. My research focuses on understanding interdisciplinary interactions during R&D. I am interested in understanding if, when, how, etc., people do research across disciplinary lines - when you are working with someone that is not in your home branch or group. So, as a part of this, I need to collect some real live examples from practicing engineers.
- Your examples will be used to add realism to my study. So please be as descriptive as possible. And note that I will be pretty quiet during the interview. I really want to focus on understanding your experience, so I will not be sharing much or commenting on what you say. I'd like to hear your stories of your experiences.

- Given that these are real examples, there are no right or wrong answers to any question that I ask you. I really just want to hear how it really is in your experience.
- I will also give you open time throughout the interview to think about your answers. So, please take the time you need during the interview to think or remember something. If you need me to clarify a question, please ask.
- I have planned about an hour for this interview.

Do you have any questions before we begin?

1 min 30 seconds

About 4 minutes total of introduction

Recording Start

Warm-up

Social, relaxed question

1) During the interview, I'd like you to describe in as much detail as you can remember, your experiences in working with people outside of your home technical discipline. For example, people from a different branch, group, department, division, or directorate, or site.
2) I'll use the word cross-disciplinary to describe these types of experiences.
3) So, first of all, I'd like to get a little bit of background.
   A) Please tell me the name of your home technical discipline.
   B) What is the name of the organization?

4) How long have you worked in this field?
5) What is your role or title, official or unofficial, in the organization?

6) Please tell me a little about what you do.

Middle

7) I'm interesting in hearing about an experience you had in working with someone outside of (use their word)? (Pause) Please tell me about it.
   A) *Only if needed:* For example, did you ever work with someone who is not a (…)? Such as (provide examples)? What happened when worked with them?
8) Mmmm,… Do you have another example of working with people from outside your technical discipline?

The task

9) When you worked with (…) what was your goal when you'd get together?

10) Can you describe what challenges you may have faced in getting …..?

11) So, tell me a bit more about what you needed from the other people when you met?
   A) Cluelessly… Are you able to get this information in another way? (Pause)

12) uh huh….   So, now I'd like to hear more about what you gained from the experience? When you think back about it, (pause)… Can you describe, what you may have gotten from the experience?
   A) When you consider the overall project or organization, (pause) how was your interaction with the other disciplines/groups helpful to the overall project or organization?

13) I'm also interested in learning about what aspects of the interactions with the other discipline were not so helpful?

14) So, when you think about your time with the other group/people/(their word)…. (pause) can you describe what aspects of the interactions with them were particularly difficult or challenging?

15) How do you think these challenges may have impacted the overall organization or project? What do you think suffered because of these challenges?

So, now I want to shift to talking a bit about the longer term.

16) So when you consider your career, how did your interactions with (…) impact your career?

17) Can you give me some examples of what aspects of your work changed based on the interactions with .(…)?

I'd like to get to some of the mechanics of your interactions…

18) I'd love to hear more about the setting when you worked with them:
    A) How many people were involved?
    B) Was there a facilitator?
    C) Where did you meet them?
    D) How far away are they from your office or lab?
       i)   How does distance play a role in how you interact with them?
    E) Where these formal presentations or informal meetings?

19) Can you describe what prompted your work with them initially? How did you meet them?

20) Can you walk me through (*again*) HOW you communicated with them? Like I'm interested in hearing about what electronic means or what documents, or what verbal means you used.

21) Can you describe HOW internal processes or policies influenced your interactions with other disciplines – positively or negatively? Internal checks and balances. What required procedures did you follow?
    A) *Get the other side… So what about any negative / positive influences?*

22) What about people that may have influenced your interactions… where there particular people that were particularly influential?   Good or bad?
   A) *How were they influential?*
   B) *Can you tell me a bit more about what did they that was so helpful or hurtful?*

23) Did   a   particular   person   tend   to   facilitate   the   meetings? How did they do it?'
24) What's the role of meetings in these interchanges?
25) Did the interchanges happen serendipitously, unscheduled?

If they don't get to it….   I'd like to hear about the roles of systems analysis and multidisciplinary optimization in these interactions

26) Was the person that initiated or maintained your interaction with another discipline someone from the systems analysis or MDO group?

27) How important was the role of the systems analysis/MDO person?
   A) *Can you describe what they did as part of your interactions with the other discipline?*
   B) *Can you tell me a bit about what aspects of the interactions they may not have or were unable to address?*

So we're almost done….   I wanted to wrap up by getting some of your recommendations.

28) Based on what we've talked about and your really interesting experiences, what ideas or recommendations you would have for improving cross-disciplinary interactions in research?

29) Do you have anything else you'd like to add about cross-disciplinary research?
30) What did I miss?
31) Anything I should have asked you that I didn't?

32) Do you have any questions for me?

Thank you so much. This was great! I learned a lot. I wonder if it would be OK if I contacted you if I missed something?

So, as I mentioned I'll remove all identifying information from the transcripts of this tape. And then I'll destroy the tape. <u>**End recording**</u>

<u>Immediate Post-Interview Notes:</u>

Where we met

Describe the setting more

My Initial reactions

Their comfort/discomfort?

What did they have the strongest reaction to?

Anything about the place/venue/person/happenings that may have influenced the interview?

Appendix 3 Human Subjects Research Approvals

Subject: **eResearch Notification: Notice of Exemption**
From: eresearch@umich.edu <eresearch@umich.edu>
To: annamrm@umich.edu <annamrm@umich.edu>
Date: Dec 13, 2011 3:38 pm

UNIVERSITY OF MICHIGAN
eResearch.umich.edu

Health Sciences and Behavioral Sciences Institutional Review Board • 540 East Liberty Street, Suite 202, Ann Arbor, MI 48104-2210 • phone (734) 936-0933 • fax (734) 998-9171 • irbhsbs@umich.edu

To: Anna-Maria McGowan

From:

Richard   Redman

Cc:

Anna-Maria   McGowan
Colleen   Seifert

Subject: Notice of Exemption for [HUM00058914]

SUBMISSION INFORMATION:
Title: Interdisciplinary Interactions during R&D of Large-Scale Complex Engineered Systems
Full Study Title (if applicable):
Study eResearch ID: HUM00058914
Date of this Notification from IRB: 12/13/2011
Date of IRB Exempt Determination: 12/13/2011
UM Federalwide Assurance: FWA00004969 expiring on 6/13/2014
OHRP IRB Registration Number(s): IRB00000246

IRB EXEMPTION STATUS:
The IRB HSBS has reviewed the study referenced above and determined that, as currently described, it is exempt from ongoing IRB review, per the following federal exemption category:

> **EXEMPTION #2 of the 45 CFR 46.101.(b):**
> Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Note that the study is considered exempt as long as any changes to the use of human subjects (including their

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data) remain within the scope of the exemption category above. Any proposed changes that may exceed the scope of this category, or the approval conditions of any other non-IRB reviewing committees, must be submitted as an amendment through eResearch.

Although an exemption determination eliminates the need for ongoing IRB review and approval, you still have an obligation to understand and abide by generally accepted principles of responsible and ethical conduct of research. Examples of these principles can be found in the Belmont Report as well as in guidance from professional societies and scientific organizations.

SUBMITTING AMENDMENTS VIA eRESEARCH:
You can access the online forms for amendments in the eResearch workspace for this exempt study, referenced above.

ACCESSING EXEMPT STUDIES IN eRESEARCH:
Click the "Exempt and Not Regulated" tab in your eResearch home workspace to access this exempt study.

Richard Redman
Chair, IRB HSBS

National Aeronautics and
Space Administration

Langley Research Center
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January 10, 2012

Anna-Maria McGowan
Aeronautics Research Directorate
Mail Stop 254
6 East Taylor Street
NASA Langley Research Center
Hampton, VA 23681-2199

Subject: Interdisciplinary Interactions during R&D of Large-Scale Complex Engineered Systems [HUM00058914]

Ms. McGowan,

IRB members received and reviewed the Notice of Exemption, regarding the subject study, from the University of Michigan. The board concurs with their finding of the study as exempt from further IRB review. This memo serves to document that exemption.

If significant changes are made to the study or its procedures, that may change its status, a subsequent review and approval by the LaRC IRB must be obtained prior to implementation.

Jeffrey S. Hill
Chairman, Institutional Review Board
MS 285, NASA Langley Research Center

Cc:
Patricia G. Cowin, CIH, CSP
Vice Chair, Institutional Review Board
Safety and Facility Assurance Office, MS 305

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