Connected Design Rationale:

Modeling and Measuring Engineering Design Learning

By

Golnaz Arastoopour Irgens

A dissertation submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy
(Educational Psychology)

at the
UNIVERSITY OF WISCONSIN-MADISON
2017

Date of Final Oral Examination: 05/02/2017

The dissertation is approved by the following members of the dissertation committee:

David Williamson Shaffer, Professor, Educational Psychology, Learning Sciences
Naomi Chesler, Professor, Biomedical Engineering
Martina Rau, Professor, Educational Psychology, Learning Sciences
Peter Steiner, Professor, Educational Psychology, Quantitative Methods
Sheri Sheppard, Professor, Mechanical Engineering

For My Dad, My Hero

ACKNOWLEDGEMENTS

This work would not have been possible without all the collaboration, support, and encouragement from so many people. I have been extremely fortunate to work with the Epistemic Games Research Group for the last seven years. Thank you to my advisor, David Williamson Shaffer, for his mentorship, motivation, and immense knowledge. Thank you to Naomi Chesler, for her encouragement and guidance throughout graduate school. I would also like to express my gratitude for all the support from past and present members of the group: Gina Svarovsky, David Hatfield, Elizabeth Bagley, Padraig Nash, Cynthia D'Angelo, Monica Bryant, Jenny Saucerman, Wesley Collier, Dan Tetrick, Hong Bui, Amanda Geske, Bob Pierce, Hannah Kinley, Cody Marquart, Andrew Ruis, Sasha Rosser, Bryan Rosen, Peter Quigley, César Hinojosa, Brendan Eagan, Amanda Siebert-Evenstone, Tiffany Herder, and (last but never least) Zach Swiecki.

I am grateful to my dissertation committee members: David Williamson Shaffer, Naomi Chesler, Martina Rau, Peter Steiner, and Sheri Sheppard for their invaluable insights and feedback during this process. I would also like to thank the staff in the Educational Psychology Department and the Wisconsin Center for Education Research for making this degree possible.

Further, I would like to thank the different organizations that made the research described in this dissertation possible. Thank you to all the teachers, instructors, and collaborators who believed in the potential of *Nephrotex* and took risks to implement the program at their institutions. In addition, this was funded in part by National Science Foundation (DRL-0918409, DRL-0946372, DRL-1247262, DRL-1418288, DUE-0919347, DUE-1225885, EEC-1232656, EEC-1340402, REC-0347000), the MacArthur Foundation, the Spencer Foundation, the Wisconsin Alumni Research Foundation, and the Office of the Vice Chancellor for Research and Graduate

Education at the University of Wisconsin-Madison. The opinions, findings, and conclusions do not reflect the views of the funding agencies, cooperating institutions, or other individuals.

My appreciation also extends to my support system in Wisconsin and all over the country. A special shout out to Libby Pier and Paige Mission, who know what an exciting yet arduous process it is to earn a PhD. Thank you to my dad in Chicago, Hamid Arastoopour, who keeps me grounded. Thank you to my mother in California, Soheila Norolouni, who provides unconditional love. And thank you to my sister, Nassim Arastoopour, who I can laugh with for hours, and my first friend Parisa Gerami, who helps me see the silver lining when I'm in the cloud.

Finally, it is with my whole heart that I thank my husband, Allen Arastoopour Irgens, who is my everything. His continuous love and support helps make anything possible.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

SHORTAGE OF ENGINEERS

Every century has its own set of social and economic problems, and the twenty-first century is no exception. More than one hundred years ago, society was confronted with the tuberculosis epidemic and sanitation issues; today we are faced with finding alternative energy sources and securing cyberspace. At the same time, the twenty-first century is a unique period as the development and use of technology is changing at an unparalleled pace (Friedman, 2016). In just a few decades, the technology industry has developed products that rapidly purify water, instantly stream multimedia entertainment, and allow us to network with billions of people around the world. With the industrial changes that this century brings, future generations of engineers will need to develop a form of design thinking that allows them to understand the complex social and physical relationships that enable modern technologies to function.

Unfortunately, at the close of the twentieth century, the federal government and various research institutions declared that the United States had a shortage of engineers (Atkinson, 1990; National Research Council, 1996; National Science Foundation, 1993; Seymour & Hewitt, 1997). Reports showed that higher education institutions were not graduating enough engineers to fill the vast number of available technical jobs. As a result, many U.S. companies hired workers from other countries to fill these jobs which threatened the economic and competitive state of the country. This occurred at a particularly critical time when the economy was becoming increasingly less local, more global, and vastly more technologically dependent (Friedman, 2005).

In the past decade, recent reports are presenting a more positive outlook. According to the National Science Foundation (2014), the number of engineering graduates has been steadily increasing since 2000. As a result, the numbers have reversed—there are now more engineering graduates than there are engineering jobs (Carnevale, Smith, & Melton, 2011). However, although the data show an abundance of engineering graduates, companies still maintain that there is a shortage of engineers for hire.

This discrepancy is accounted for by examining the number of people who graduate with an engineering degree compared with the number of people who enter the engineering workforce—only 70% of engineering graduates choose to work in a science, technology, engineering, or mathematics (STEM) field (Snyder, Dillow, & Hoffman, 2009). In a report on the state of STEM education and the workforce, Carnevale and colleagues (2011) stated that "students will not select science and math careers simply because they are capable of doing so. Work interests play a key role in diverting students… More attention must be paid to the role of work interests in forming student and worker desires" (p 75). Thus, the newest problem this decade faces regarding engineering attrition is that students are losing interest in engineering after college and, in turn, not entering the STEM workforce.

In response to the economic consequences associated with a lack of interest in joining the engineering workforce, federal agencies have created lists of societal problems that require solutions from the STEM community. For example, the National Academy of Engineers (NAE) published a set of *21st century grand challenges* that focused on engineering solutions (National Academy of Engineering, 2008). The report highlighted engineering's greatest accomplishments in the last century such as widely available electricity, aircrafts, and the development of Internet.

The report also posed several challenges for the current century such as energy scarcity, pandemic diseases, and terrorist violence. The NAE argued that as the population grows and its needs increase so will the challenges that society faces and that human concerns surrounding sustainability, health, and safety require engineering solutions to improve the quality of life.

21ST CENTURY DESIGN EDUCATION AND ASSESSMENT

The NAE's introduction of 21st century grand challenges may be a good motivator to encourage engineering graduates to join the workforce, but solely being motivated is not sufficient—engineers must have innovative, 21st century *skills* to tackle such challenges (Galloway, 2007; Sheppard, Pellegrino, & Olds, 2008). The new-century engineer should have strong analytical skills, be able to communicate and collaborate, develop creative solutions, and be aware of the growing interdependencies between technology and the economy (National Academy of Engineering, 2004; Sheppard, Macatangay, Colby, & Sullivan, 2009). Future engineers must design innovative solutions with realistic economic, political, and technical constraints in mind and be able to communicate their solutions to the general public. In short, to solve the complex problems of this century, future generations of engineers must be 21st century designers.

The field of engineering education has embraced this challenge of educating the new-century engineer and has made design a central component of engineering education (Atman, Eris, McDonnell, Cardella, & Borgford-Parnell, 2014; Dym, Agogino, Eris, Frey, & Leifer, 2005). As Sheppard and colleagues (2009) suggest, "guiding students to learn 'design thinking' and the design process, so central to the professional practice, is the responsibility of engineering education" (p. 98). Consequently, if design is so central to engineering, then educators and researchers need methods for teaching and assessing design skill development.

However, as Razzouk and Shute (2012) argue, very few valid performance-based assessments of design thinking skills exist, which limits the ability to collect evidence about students' development of such skills. Existing traditional assessments tend to measure whether a student possesses a piece of knowledge and not whether they can apply their understanding or build new knowledge from their existing understanding of the domain (Silva, 2008). As a result, modeling and measuring the complex nature of authentic design learning still remains a challenge. Thus, the goal of this dissertation work is to merge current learning sciences research with design education to develop an approach for modeling and measuring design thinking.

I approach this problem by framing design work as fundamentally requiring two key skills: (1) making appropriate *design moves*—actions taken during the design process (Schön, 1983) and (2) providing explicit *design rationale*—justifications for chosen design moves (Rittel, 1987). Moreover, learning sciences research argues that learning a practice, such as engineering design, centers on understanding the connections among domain-relevant elements rather than measuring isolated instances of skills and knowledge (diSessa, 1993; Linn, 2006; Shaffer, 2006, 2007a). Building on this work, I propose that the critical piece of measuring design thinking centers on the ways in which students understand the connected relationships among design moves and design rationale—what I call a *connected design rationale*.

To explore this idea, I first qualitatively investigate how engineers and interns make connections among moves and rationale in their talk and interactions in a real-world internship program at an engineering company. Then, I examine such connections in more detail by examining student work in a virtual internship program, *Nephrotex*, which captures student work in digital forms. To measure connections among moves and rationale, I use epistemic network analysis (ENA), a discourse network analysis tool which measures the patterns of relationships among domain-relevant discourse components. Using ENA, I compare the discourse networks of first-year undergraduate students in the virtual internship and the discourse networks of professional engineers in the real-world internship to determine if measuring connected design rationale reveals meaningful differences between expert and novice design thinking in two different design learning contexts. By better understanding the development of design skills, my dissertation will begin to shed light on an implicit cognitive process that is fundamental to 21st century design education.

DISSERTATION OVERVIEW

This dissertation work is presented in the following six chapters. Chapter One, this chapter, introduces the topic and an overview of the dissertation. In Chapter Two, I present the theoretical framework for the study. This chapter argues for modeling and measuring design thinking as connections among moves and rationale in discourse. Chapters Three, Four, and Five outlines the settings, data collection, analysis techniques, and results in this study. Results from the analysis demonstrate that (1) professional engineers have more sophisticated and meaningful patterns of connections among moves and rationale than interns, (2) that high-outcome students in the virtual internship, *Nephrotex,* had more sophisticated and meaningful patterns than low-outcome students, and that (3) high-outcome students in the virtual internship, *Nephrotex*, had connected discourse patterns that were more like those of professional engineers than low-outcome students. Finally, in Chapter Six, I present a discussion of the study’s findings, limitations, and implications.

CHAPTER 2

THEORETICAL FRAMEWORK

ENGINEERING DESIGN PRACTICE

ILL-STRUCTURED DESIGN PROBLEMS

Design is the central and defining activity of engineering (Simon, 1996). In modern society, engineering design can be defined as the process of creating a description for products rather than producing the artifacts themselves. Simon (1996) describes design as devising artifacts to attain goals. Similarly, Cross (1994) claims that all engineering design problems identify a goal, constraints within which the goal must be achieved, and some criteria by which a successful solution must be recognized. Expanding on these ideas, Ulrich (2011) states that design is a problem-solving activity that begins with a perception of a gap in a user experience. This gap is the motivation for the plan for a new artifact. In this view, the design solution centers on solving a problem to meet a user's need. Finally, Dym and others (2005) provide a more holistic definition of engineering design as "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (p. 104). That is, design is what Rittel and Webber (1973) call "plan-making," a process by which engineers create descriptions for technical artifacts to address a need in society.

The details of the process by which an engineer designs a product, however, are complex and multi-faceted (Cross, 1994; Ulrich & Eppinger, 2011). Lawson (2005) claims that "the designers of today can no longer to be trained to follow a set of procedures" (p. 6) because most situations that designers address are *ill-structured problems*—issues that cannot be solved using pre-defined methods. Such problems typically have conflicting goals, develop unexpected complications, and have multiple solution paths (Cross, 1994; Dym, 1994; Jonassen, 2000; Rittel & Webber, 1973). Jonassen and colleagues (2006) argue that although problems in an engineering workplace may initially seem well-structured, as constraints and unanticipated problems emerge, it becomes apparent that design problems are wholly ill-structured in nature. For example, they describe a mechanical engineer who designed a device to measure the temperature and flow of a liquid coming out of a large container. Calculating temperature and flow is a straight-forward task because engineers have thermostats and flow measuring devices. However, during this design project, the engineer realized that in order to install the thermostat device, the tank needed to be sealed, which would stop the flow completely. As a result, the engineer needed to rethink how to install the thermostat device such that it would effectively measure the temperature but not constrain the flow in the tank. Therefore, although engineering design projects contain well-structured components that involve following procedures, such as measuring and recording temperature values, the broader design problems that engineers solve are inherently ill-structured and complex, which require engineers to think and rethink through potential solutions.

DESIGN MOVES AND RATIONALE

Schön (1984, 1987, 1988) examined engineers, architects, and other professionals engaged in ill-formed design work, and based on these investigations, he described the design process as a series of making *design moves*—actions taken during the design process to help the designer reach a final solution. According to Schön's model, when designers execute such moves, their understanding of the design scenario transforms as a result of generating and interpreting new representations of the design (Gero & Kannengiesser, 2008). The previous example of the mechanical engineer from Jonassen and colleagues (2006) can be used to illustrate what Schön calls “seeing-moving-seeing” (Schön & Wiggins, 1992). The first act of “seeing” occurs when the engineer decides to build a device that measures both flow and temperature from a large container. So, the engineer made a move: he planned to install an existing thermostat device. This move led to a second instance of “seeing” in which the engineer realized the consequence of this move—that installing the existing thermostat device would require the tank to be sealed and interfered with the flow of the container. Design moves such as the ones in this example are common in engineering design practice and such engineering moves may include conducting research on the potential components of a design, modifying a design drawing, and selecting a component for a product (Schön, 1983). Thus, design moves are suggested or enacted actions which are motivated by reflections on a design scenario.

Schön’s “seeing and moving” portrays design as a reflective, iterative process and argues that seeing unintended consequences of current actions are crucial stimuli for future actions. McCall and Burge (2016) claim, however, that designers may not always spontaneously “see” the consequences of a decision or understand why unanticipated consequences exist, which is especially true of novice or student designers (McCall, Fischer, & Morch, 1989). In turn, Rittel (1987) argues that what facilitates and supports the iterative movement of reflection and action through the design process is relying on explicit justifications for design moves. Providing explicit argumentation may help reduce the chance of overlooking critical aspects of a problem, increase the chance of seeing connections to other similar problem scenarios, and facilitate communication among a design team or stakeholders (Noble & Rittel, 1988). This notion of design reasoning as a process of argumentation is now widely known as *design rationale*. Following this line of work, a number of researchers have suggested design rationale provides the fundamental logic of design moves and is the basis for decision-making and actions in engineering (Branham et al., 2007; Burge & Brown, 1999; Conklin & Yakemovic, 1991; Lee, 1997; Shum & Hammond, 1994). In practice, engineers provide rationale for design moves by referencing technical knowledge, such as mathematical formulas, scientific proofs, or conducting small-scale empirical studies (Garcia & Howard, 2009). They may also justify moves through non-technical constraints, such as such as time restrictions, budget requirements, and limited personnel (Marples, 1961; Papalambros & Georgiopoulos, 2006). Design rationale is made explicit through conversational interactions (Bucciarelli, 1994) or in written reports (Lee & Lai, 1991) during the design process.

Taken altogether, engineering design practice centers on two critical skills:

> (1) the ability to make appropriate design moves, meaning knowing how and when to take appropriate actions during the design process, and
>
> (2) the ability to use design rationale, meaning knowing how and when to provide explicit justifications for design moves.

In other words, designers must be able to imagine and enact potential design moves and provide justifications for why particular moves are appropriate.

HOW ENGINEERS LEARN TO DESIGN

REFLECTIVE DESIGN PRACTICA

Because design is so central to the engineering practice, it is also central to engineering education. Research in engineering education suggests that design is most effectively learned through experience in *professional practica*, spaces where students participate in a simulation of the practice under the guidance of senior practitioners (ABET, 2014; Atman et al., 2014;

Harrisberger, Heydinger, Seeley, & Talburtt, 1976; Johri, 2010). Particularly relevant to design education, Schön (1987) argues practica offer a space for professionals-in-training to reflect on their work by engaging in authentic, ill-formed tasks. In a reflective practicum, a student must make moves to learn how to design even when he does not understand what designing means. He is caught in a *paradox of learning* which Schön describes as a situation in which, “a student cannot at first understand what he needs to learn, can learn it only by educating himself, and can educate himself only by beginning to do what he does yet understand” (pg. 93).

Of course, a student does not resolve this paradox alone; she receives guidance from more knowledgeable mentors in the practice. Mentors examine student moves and try to discern what the student understands, what she already knows how to do, and what the difficulties are. The mentor then coaches the student through the design process by modeling design practice and ways of thinking about the problem (Collins, Brown, & Holum, 1991). Through such interactions, the mentor and the student are jointly engaging in *reflection-ON-action*—reflecting and evaluating moves *after* they are made (Schön, 1983, 1987). This process of reflecting on past actions is repeated through interactions with the mentor and student in the practicum. The goal is for the student to eventually engage in *reflection-IN-action*—reflecting and evaluating moves *while* they are being made. In other words, reflective practica are spaces where novices learn how to engage in specific acts of “seeing-moving-seeing”—positing potential actions and considering the consequences on the design and the implications on future moves.

Such reflective interactions between mentors and novices can be classified as *participant structures,* which Palincsar and Lehrer (2004) define as a way to structure social interactions and norms in an educational setting. Specific to a reflective practicum, Shaffer (2005a) describes participant structures as “social arrangements that are tightly bound to the practices of a specific domain and the particular activities of the specific practicum… or, more precisely, the recurrent pattern of involvement that structures a particular kind of situation within a given practice.” For example, Shaffer (2007b) refers to *desk crits* as participants structures in architectural practices. In desk crits, a peer or teacher acts as a critic and consults with a student on her progress. The student first presents some work to the consultant, possibly citing some areas of concern. The critic then asks the student clarifying questions about their process and identifies potential problems and next steps for the student to continue her work.

A reflective design practicum, then, is a collection of participant structures in which mentors and novices engage in reflection-on-action. It is through such interactions that novice learn how to make moves and provide rationale in ways that are representative of mature practitioners.

REAL-WORLD INTERNSHIPS

In undergraduate education, one common example of engineering design practica are *real-world internships* in which students complete their design work at existing engineering companies. Such work-based learning programs, also known as *cooperative education* or *co-ops*, give students an opportunity to work alongside senior practitioners who mentor them through their projects and allow students to experience realistic aspects of design work such as working in teams, communicating with clients, and iterating through potential solutions (Zoltowski, Oakes, & Cardella, 2012). A real-world internship offers students an opportunity to apply their scientific and technical skills, but also learn conflict resolution skills, how to manage job stress, and the consequences of missing deadlines in the workplace (Tener, Winstead, & Smaglik, 2001). If the internship provides a space for students to engage with realistic design tasks and to experiment with their own professional behavior, students begin to develop a professional engineering identity (Dehing, Jochems, & Baartman, 2013) and because of this identity development, are more likely to persist in the engineering field (O'Connor et al., 2007).

Although real-world internships and co-op education are common among undergraduate engineering education programs, very little work has been done on how students learn design in workplace settings[1]. The research that has been done on design learning in internships has examined student affect towards their engineering work by distributing surveys to or conducting interviews with students after their internship experiences (Jiang, Wai, & Lee, 2015; Ralph, Walker, & Wimmer, 2009). For example, Stevens and colleagues (2008) conducted an ethnographic study in which they interviewed engineering students over the course of four years to determine how internship and coursework experience influenced their decision to remain or switch out of an engineering major. Such studies provide information on student experiences with engineering design inside and outside the classroom, but they do not collect interview or observational data during the internship process and thus, do not provide information on how student design learning emerges and develops within professional practice and internship settings. Currently in both learning sciences and engineering education, there is little ethnographic work examining how student learn engineering design in a workplace setting and it is critical that such

---

[1] Not only is there a lack of research on how students learn engineering design in professional contexts, Trevelyan (2010) and others (Downey & Lucena, 2004; Vinck, 2003) claim that there is a lack of research on engineering professional practices more generally. The few examples of ethnographic work on engineering professional practice include Bucciarelli (1988, 1994), Suchman (2000), Anderson and colleagues (2010), and Johri (2011).

studies are conducted in order to better understand engineering design learning (Johri & Olds, 2011).

VIRTUAL INTERNSHIPS

Although studies of real-world internships could facilitate an understanding of how students learn design in authentic workplace environments, conducting detailed ethnographic studies in professional settings has significant challenges. The duration and cost of such studies can be high and gaining access to professional organizations can be time-consuming and difficult (Monahan & Fisher, 2014). To address this issue, Hsu (2014) and others (Boellstorff, 2013; Burrell, 2012) suggest expanding ethnographic methods to digital social environments, such as online forums or social networking sites. Hsu (2014) argues that one of the main advantages of digital ethnography is that data collection and computational analyses allow for the examination of a large corpus of information, which in turn allows for the ability of a rich and detailed analysis of human behavior—a form of augmented ethnography. Similarly, Baker (2016; 2009) argues that collecting and analyzing data from digital and virtual learning environments can enhance existing learning theories by "improving models of a domain's knowledge structure" (2009, p. 7). Thus, collecting digital data from virtual learning environments and using computational methods to analyze such data could potentially augment and improve upon findings from traditional ethnographic studies of workplace environments.

One example of such virtual learning environments is *virtual internships*, online simulations of authentic practice where all student work is recorded digitally (Chesler et al., 2015). In the engineering virtual internship *Nephrotex* (Arastoopour et al., 2012; Chesler, Arastoopour, D'Angelo, Bagley, & Shaffer, 2012), first-year students work as engineering interns for a fictitious biotechnology company to design an ultrafiltration membrane for hemodialysis equipment. Interns work in teams performing tasks that they would do in an ideal internship: reading and analyzing research reports, designing and performing experiments, responding to client and stakeholder requirements, and proposing and justifying design prototypes, all within a self-contained workplace simulation. At various points during the design process, students are asked to record their design process in their individual engineering notebook. The online system digitally tracks all collaborative conversations among team members, individual's entries in their digital engineering notebook, and every object that an individual has clicked. Such records of student work provide an opportunity for rich analysis of student design learning in an authentic environment at a larger scale than with traditional ethnographic studies and as such, could provide more insight into how students learn engineering design in professional practica settings.

MODELING DESIGN LEARNING

CONNECTED LEARNING

While characterizing design work and creating opportunities for design learning are important, a greater challenge is how to model the complexity of design thinking as it emerges in practice (R. Adams, Daly, Mann, & Dall'Alba, 2011). Learning sciences research suggests that complex thinking is characterized not by isolated pieces of knowledge and skill, but by the organization of and relationships among domain-relevant knowledge and skills (Atman, Chimka, Bursic, & Nachtmann, 1999; Bransford, Brown, & Cocking, 1999; Chi, Feltovich, & Glaser, 1981; Dreyfus & Dreyfus, 2005; Jacobson & Wilensky, 2015; Wilensky & Resnick, 1999).

diSessa (1988) claims that before developing a complex understanding of physics, novice learners begin with an intuitive understanding of independent concepts called *phenomenological* *prims,* or *p-prims* for short. Such p-prims are based on people's common-sense experiences and are primitive in the sense that they provide a surface-level explanation of physics concepts. For example, a p-prim explanation of an object moving faster could be that "something is working harder on the object" to move it faster (diSessa, Gillespie, & Esterly, 2004). diSessa (1993) argues that this knowledge system of p-prims starts as distributed and fragmented, but then evolves to one that is coherent and connected to more advanced physical principles. This linked understanding of concepts represents a deeper and more holistic understanding that is representative of mature physics understanding.

Like diSessa's notion of p-prims, Linn and colleagues (1995; 2004) found that students first generate ideas and understandings about the world through personal experiences. Through instruction and discussion with other classmates, students "sort out" their fleeting ideas in various ways until they build strong connections to use as a basis for future learning. In other words, learning is categorized as developing a repertoire of ideas by adding new concepts from instruction and, most importantly, by making connections among ideas. Such connections become more advanced as students develop specialized criteria for evaluating ideas and "formulate an increasingly linked set of views about any phenomenon" (Linn, 2006, p. 243). Linn and colleagues (2004) describe this as the *knowledge integration* framework which argues that complex learning is a process of developing a *knowledge web*: relations among concepts, principles, procedures, conjectures, and experiences.

One of the main motivations for Linn's work is to use the knowledge integration framework as a tool for improving science instruction (Linn, 2006). Rooted in this framework, the design of science instruction centers on three principles. First, the curriculum is designed to elicit current ideas from the various contexts that students encounter and then use to develop connections among ideas. Second, the curriculum is designed to add new, normative ideas that can be integrated and connected with their personal understanding of science. Third, the curriculum facilitates opportunities for reflection such that students can integrate current and new ideas together into coherent and connected patterns of science understanding. Thus, building a connected and personally meaningful knowledge web of science ideas is at center of the knowledge integration framework and curriculum development.

Relatedly, Shaffer (2004, 2006, 2007) has characterized complex learning in terms of a connected *epistemic frame*—ways of knowing, thinking, and being that are linked together. However, unlike diSessa and Linn's work, Shaffer characterizes complex thinking in professional *cultures*, such as engineering (Chesler, Arastoopour, D'Angelo, Bagley, & Shaffer, 2013), urban planning (Bagley & Shaffer, 2009), or journalism (Hatfield & Shaffer, 2006). In this view, becoming part of a professional culture means acquiring a particular Discourse (with a capital D)—the ways people talk, read, write, think, believe, act, and interact within a distinctive group (Gee, 2004, 2015). For example, the Discourse of professional biology might include reading the sentence, "Hornworm growth displays a significant amount of variation," in an academic article. To understand the meaning of this sentence within the context of the Discourse, a biologist must realize that "significant" may not mean "a large amount," but instead refers to statistical measures of "significance" and what is classified as significant variation and what is not (Gee, 2004, 2013). In other words, a Discourse constitutes specific ways of enacting socially significant meanings that are situated with the context of a practice.

An epistemic frame, then, is the grammar of that Discourse: a formal configuration of the Discourse exhibited by learners when they become acculturated into a practice (Shaffer, 2005c). More than just a collection of different elements, epistemic frame theory focuses on the ways in which specific elements are used together during complex thinking and problem solving related to a practice. For example, members who fully participate in a practice rely on domain-specific skills and knowledge to make and justify decisions, have characteristics that define their identities as members of the group, and draw on a set of values to classify important issues and problems in the field. Developing an epistemic frame means understanding and enacting the relationships among skills, knowledge, identities, values, and epistemological elements that are characteristic of the community, and thus developing expertise related to ways of knowing and being within a practice.

CONNECTED DESIGN RATIONALE

As the learning sciences research suggests, complex learning is not the accumulation of isolated pieces of knowledge but instead, is the development of relationships among domain-specific concepts and ways of thinking. In this view, learning the practice of engineering design is not a stepwise procedure of accumulating skills nor is it merely making moves and providing rationale, but rather, design expertise is developed by understanding connections among design practice Discourse. More specifically, learning design is learning which moves are linked to which rationale and the complex web of relationships among moves and rationale in particular design problem situations. Such relationships among moves and rationale not only help the designer imagine potential scenarios and consequences, but also to effectively choose which moves to enact and as a result, progress through the design problem. Thus, learning to be a professional designer requires knowing how to make and justify design moves, but more precisely, it requires an understanding of the complex relationships among enacted and imagined moves and rationale in design situations—what I am calling a *connected design rationale*.

Skilled designers exhibit a connected design rationale when they reflect on the problem at hand and can implement and justify the appropriate moves to develop a solution. For instance, if an undergraduate engineering student is on a design team that is designing handlebars for a bicycle, he or she might first gather information and document their design process to better understand the design problem. Then, he or she could propose two potential next steps to team members in a design meeting: to take a vote among team members as to which material to use in the design or to use simulation software to experimentally test the viability of several materials. The student engineer could justify the experimental approach by claiming that implementing this approach would allow the team to economically eliminate materials that are not viable, but also verify the properties of the materials. Ultimately the team may decide to conduct experimental tests as opposed to taking a vote because of the rationale provided.

In this example, the student makes two initial moves: gathering information and documenting the design process. The student justifies documenting the process and gathering information because it will help to better understand the problem (Figure 1a). Once these two moves are enacted and the student has a better understanding of the problem, this leads to two potential moves: taking a vote or conducting experimental tests to choose a material and continuing to document the process (Figure 1b). Ultimately, the team decides to conduct experimental tests because this move has three linked justifications: that experimental testing using a simulation will help the team narrow down their material choices, that it is more economical than other approaches, and that the simulation will help verify critical properties of each material. The other option of taking a vote to determine which material to use was not enacted because there was not a strong enough rationale to enact such a move (Figure 1c). The next move would then to be to choose the composite material and once again, gather more information about the problem (Figure 1d). This example reveals a short part of one engineering student's design process as a series of interconnected enacted and imagined moves and rationale as the team designs a product.

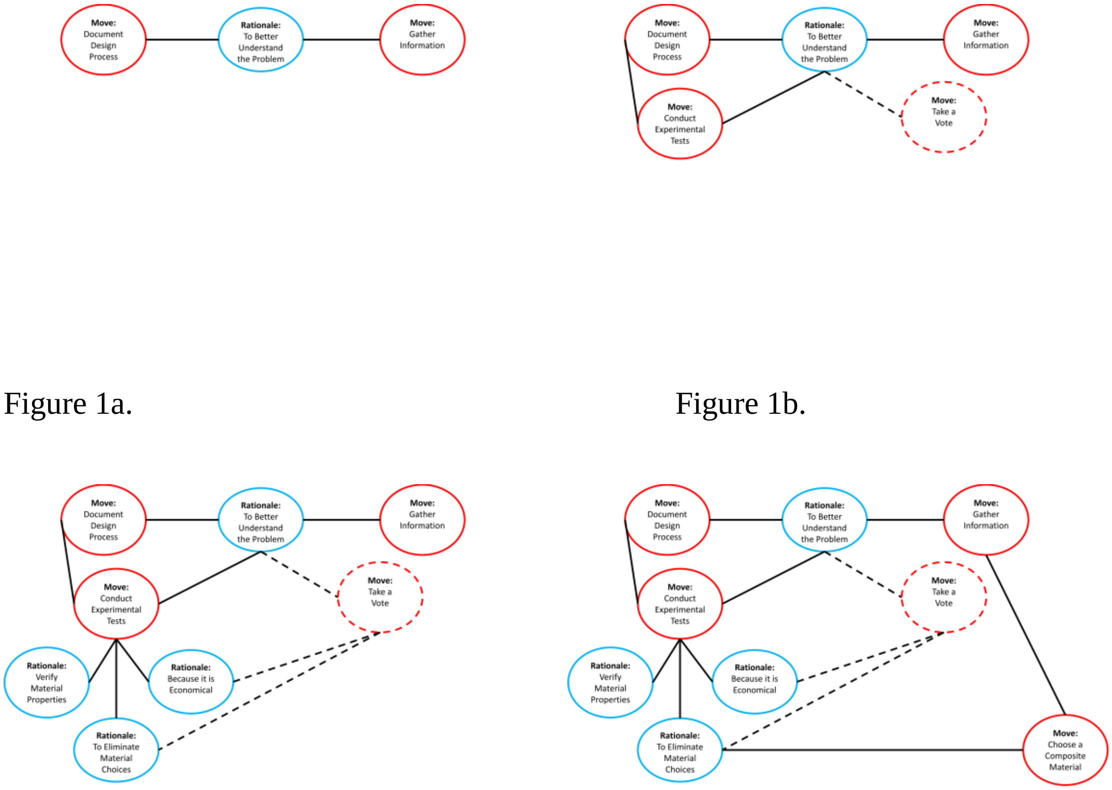


Figure 1a. Figure 1b.

Figure 1c. Figure 1d.

Figure 1 a-d. Example of a developing Connected Design Rationale. Red circles represent design moves and blue circles represent rationale. Solid lines represented enacted moves and dotted lines represent imagined or suggested moves.

Thus, connected design rationale is a proposed theoretical framework for modeling the learning that occurs in design practice and suggests that design learning is more accurately illustrated as patterns of appropriately connected moves and rationale rather than a collection of isolated skills.

MEASURING DESIGN LEARNING

EPISTEMIC NETWORK ANALYSIS

Building on epistemic frame theory and the idea of Discourse, connected design rationale is an examination of design learning which hypothesizes that expertise in design thinking can be modeled as connections among moves and rationale identified in Discourse. Such connections can be visualized as a *network* of moves and rationale that have been articulated in context of the Discourse either through written documents, conversations, or actions.

In general, network analyses trace the flow of information, uncover prominent patterns in networks, and detect the effects of such patterns (Garton, Haythornthwaite, & Wellman, 1997). In social network analysis, for example, researchers examine patterns among people's interactions, where the nodes of the network represent people and links among the nodes represent how strongly certain people are connected (Freeman, 2006). To measure connected design rationale, however, the nodes do not represent people, but rather represent one individual's moves and rationale that are relevant in a practice and the links represent that individual's strength of association among moves and rationale. This creates a Discourse network that connects the moves that people describe taking (or actually take) to the rationale for their moves.

One tool for developing such Discourse networks is *Epistemic network analysis* (ENA) (Shaffer et al., 2009; Shaffer, Collier, & Ruis, 2016; Shaffer & Ruis, 2017). ENA measures when and how often students make links between domain-relevant elements during their work. It accomplishes this by measuring the co-occurrences of Discourse elements and representing them in weighted network models. Furthermore, ENA enables researchers to compare networks both visually and through summary statistics that reflect the weighted structure of connections (Collier, Ruis, & Shaffer, 2016). In other words, researchers can use ENA to not only model Discourse networks, but also quantitatively compare the Discourse networks of various individuals and groups of people.

Because of these affordances, ENA has been used to compare the epistemic frames of mentors and learners (Bagley & Shaffer, 2009; Nash & Shaffer, 2013) and the epistemic frames of students in classrooms and practica (Hatfield, 2011). More recently, ENA has been used to model engineering design thinking by measuring the quality of Discourse among students during the design process (Arastoopour, Chesler, & Shaffer, 2014; Arastoopour, Chesler, Shaffer, & Swiecki, 2015; Arastoopour, Shaffer, Swiecki, Ruis, & Chesler, 2016). Finally, Collier and colleagues (2016) have empirically argued that using ENA to measure co-occurrences in Discourse detects meaningful differences in virtual internship data, where other methods that simply examined occurrences or frequencies were not. In this way, ENA is a tool for measuring connections in Discourse and as such, can be used to measure and quantify the development of students' and designers' connected design rationale.

IDENTIFYING DESIGN MOVES AND RATIONALE: METHODOLOGICAL LIMITATIONS

Of course, in order to use ENA to measure connected design rationale, meaningful moves and rationale must be identified within the Discourse. In previous studies on design work, researchers have identified design moves and rationale, but there are several methodological limitations in these reported studies. For example, Gilbuena (2015) and Wiltschnig (2013) identified design moves, including communication skills, experimental documentation, and referencing functional requirements, but did not explore the rationale linked to such moves. Atman and colleagues (1999, 2001) explored how particular design moves, such as identifying constraints, evaluating the problem, and sketching, vary among novices and experts but examined these moves in controlled, lab environments as opposed to authentic practica. Similarly, Dorst and Dijkhuis (1995) examined the design moves of an individual designer working for two hours on a bicycle design problem in a lab environment. In this study, the researchers also explored particular design justifications, but their work did not examine the particular *patterns of connections* designers make among particular design moves and rationale.

This body of work presents two issues. First, a variety of research approaches which identify design moves and rationale exist, but collections of designs moves and justifications vary from study to study and there is no consensus for a single collection of design moves and justifications for analyzing design skills that is applicable in all design problem scenarios and contexts. It is evident that collections of design moves and rationale are dependent on the design problem scenario and context. Second, although studies have been done to identify design moves and rationale, it is not clear the approaches in such studies would be useful for examining the *patterns of connections* among moves and rationale. For example, Gero and McNeill (1998) developed categories for various design moves, including analyzing the problem, postponing a design action, and explicitly referring to domain knowledge. The authors included one code for rationale: justifying a proposed solution. In their analyses, Gero and McNeill did examine the relationship between this one example of a justification and one example of a move, but did not explore such patterns and relationships in depth. Thus, current work on identifying design skills provides a variety of approaches, but few studies have explicitly examined the patterns of relationships among design moves and rationale.

GROUNDED THEORY

Because few studies have examined connections among design moves and rationale in Discourse, there are limited resources available for researchers to identify which patterns of moves and rationale are important in design practice. Creswell (2007, 2009) argues that when existing research approaches are not adequate and there is a general lack of knowledge regarding specific relationships among core concepts, then a *grounded theory* approach may be useful for a research study (Glaser & Strauss, 1967). Grounded theory begins with broad questions which guide the researcher through the data analysis and collection. As the data are analyzed, the researcher develops core theoretical concepts and iterates through analyses until a key theoretical concept is identified.

One of the key mechanisms behind such analyses is the development of codes: explicit labels for meaningful actions in the data. Coding the data is a “progressive process of sorting and defining and defining and sorting those scraps of collected data… that are applicable to our research purpose. By putting like-minded pieces together into data clumps, we create an organizational framework” (Glesne, 1999, p. 133). In other words, grounded codes support the researcher in developing core theoretical concepts that describe phenomena in the collected data. And, thus, related to this study, a grounded approach could identify meaningful design moves and rationale that constitute a connected design rationale.

VALIDATION OF MEASURING CONNECTED DESIGN RATIONALE

When using grounded theory and a newly proposed approach like connected design rationale to measure learning, an important question is the extent to which the approach is appropriate and accurate. Mislevy (2003) argues that when it comes to measuring learning, *validity* is the "cardinal virtue of assessment [and] is all about the degree to which empirical evidence and theoretical rationales support the adequacy and appropriateness of inferences and actions based on test scores or other modes of assessment."

Similarly, Kane (2006) and Messick (1995a, 1995b) claim that validity evaluation relies on (1) a well-defined theoretical framework which supports the use of a measurement tool, as well as (2) empirical or mathematical models that examine relationships between the measured scores and other scores associated with the targeted domain. For example, measurement approaches have been validated by comparing scores among experts and novices (W. K. Adams & Wieman, 2011). If differences are found between expert and novice scores, then such differences may illuminate critical features of domain proficiency which then become targets or learning goals for novice students (National Research Council, 2001). Bailey and Szabo (2006), for example, developed and attempted to validate a rubric for measuring engineering students' design processes. One aspect of the validation process involved distributing designs tasks to both first-year and senior engineering students and examining whether the rubric determined differences among first-year and senior students.

In addition, measurement approaches have been validated by correlating the scores from the measurement approaches with other scores which are associated with the domain. For example, Ekwaro-Osire and Orono (2007) designed and implemented a tool for peer evaluation of team members in a senior engineering design course. To validate this measurement tool, they correlated the peer evaluation scores with student's individual notebook scores and showed that high performing teams were correlated with high quality engineering notebooks and low performing teams were correlated with low quality engineering notebooks. Ekwaro-Osire and Orono's teamwork measurement tool predicted high quality engineering notebooks and thus, provided validity evidence for a new measurement tool's ability to predict other scores that are valued in the domain.

RESEARCH QUESTIONS

Connected design rationale is my theoretical approach for investigating a learner's connected understanding among design moves and rationale in design practice and particularly how such a connected understanding develops in professional practica. To validate this approach, I use ENA to build Discourse networks and compare experts' connected design rationale to high and low outcome students' connected design rationale in a virtual internship. In this dissertation, I conducted this examination in three parts.

PART ONE: REAL-WORLD INTERNSHIP

First, I examined moves and rationale in the context of a *real-world* internship program at an engineering company. This first examination captured how students interact with mentors (professional engineers) and learn design in an authentic, real-world setting. The two research questions in Part I are:

RQ1.1

Do students make connections among moves and rationale in a real-world internship?

RQ1.2

If students make connections among moves and rationale, how do such connections differ from those of expert engineers in a real-world internship?

Part Two: Virtual Internship

Second, I examined moves and rationale in the context of a *virtual* internship program, *Nephrotex,* where students work both individually and in teams to design a filtration membrane for a hemodialysis machine. I collected data in two ways: team chat logs and individual notebook entries. The discourse from the team chat logs were used to investigate connections among moves and rationale and the discourse from the individual notebook entries were used to divide students into high and low outcome groups. In Part Two, I only focus on two virtual internship students and the two research questions are:

RQ2.1

Do students make connections among moves and rationale in a virtual internship?

RQ2.2

If students make connections among moves and rationale in a virtual internship, how do the connections of a high and low outcome student differ?

Part Three: Scaling Up and Comparing the Real-World and Virtual Internship

Part Three scales up the results from Part Two, by examining 197 virtual internship students. In this part, I compared high and low outcome students (determined from their individual notebook scores) from the virtual internship to the experts from the real-world internship to determine if high-outcome students have patterns of connections among justifications and moves that are more like those of experts than low-outcome students.

RQ3

Do high-outcome virtual internship students have connections among moves and rationale that are more like those of experts in the real-world internship than low-outcome students?

CHAPTER 3

PART ONE: REAL-WORLD INTERNSHIP

METHODS

OVERVIEW

The research questions in this dissertation work are addressed by examining discourse data from professional engineers and interns in a real-world internship program and from first-year undergraduate students in a virtual internship program. In Part One, I conducted an ethnographic study of an internship program at a mid-sized company. This real-world internship data consisted of semi-structured interview transcripts from four interns and two professional engineers, as well as ethnographic field notes. I used grounded theory to develop qualitative codes which identified various moves and rationale, and then, using ENA, I investigated the connections and relationships among moves and rationale.

SETTING

I collected ethnographic data from an internship program at an engineering company, GammaCorp[2]. The GammaCorp branch which I investigated was housed in a two-story building that sits on 180 acres of land and includes employee workspaces and a production facility. The internship program was a paid program that lasts eight months. There are two cycles of the program that take place either May through January or August through April so that more experienced interns overlap with novice interns. I observed the internship program from June through August.

---

[2] Company and participant names have been replaced by pseudonyms.

For each iteration of the program, the company interviews and selects 10-15 undergraduate students. Once the students are selected for the program, they are managed by Warren, an experienced mechanical engineer who has been at GammaCorp for over 20 years. Warren assigns the students to projects which include discussing orders with customers, completing the paperwork for placing orders, and designing custom products for customers.

PARTICIPANTS AND DATA COLLECTION

At GammaCorp, there are two iterations of the internship program every year. The first group of students begins the program in January and ends in August, while the second group begins in June and finishes in December. As a result, there is an overlap period between the two groups of students from May until August. For this study, I chose to observe during this overlap period from June until August in order to observe the interaction between the novice interns and senior interns.

For this iteration of the internship program, I examined two novice interns, Alice and Bobby, and two senior interns, Marcos and Nikos. To obtain a comprehensive record of the students' daily activities, I observed one novice intern, Alice, and one senior intern, Nikos, closely for three consecutive days. In addition, I observed six professional engineers who interacted with the students at various times. To collect detailed data about the interactions between engineers and interns, I focused on two senior engineers, Warren and Zara. No other demographic information was collected about the participants. The key participants are summarized in Table 1.

Table 1. Descriptions of Participants

Student Name	**Undergraduate Major**	**Position**	**Years of Experience at GammaCorp**
Alice	Mechanical Engineer	Novice intern	2 months

Bobby	Electrical Engineer	Novice intern	2 months
Marcos	Mechanical Engineer	Senior intern	6 months
Nikos	Mechanical Engineer	Senior intern	6 months
Warren	Mechanical Engineer	Engineer & Program Director	15 years
Zara	Mechanical Engineer	Engineer	10 years

I collected data in two forms: semi-structured interviews and observational field notes.

First, I was present as an observer for ten days from June to August. During this time, I focused on participant structures, "social arrangements that are tightly bound to the practices of a specific domain and the particular activities of the specific practicum" (Shaffer, 2005b, p. 6). I observed two project management meetings and seven meetings between engineers and students. When there were no meetings or interactions to observe, I examined the employees' actions. I collected data in the form of audio recordings and field notes. Recordings were transcribed to provide a detailed record of interactions, and field notes were used to capture meaningful non-verbal aspects of the context and supplement the transcripts.

Second, I interviewed four students, Alice, Bobby, Marcos, and Nikos, to discuss their internship experience. I also interviewed two engineers, Warren and Zara, to discuss the internship program. I collected this data in the form of audio recordings which were also transcribed.

SEGMENTATION AND CODING

Observations and interviews were segmented by *utterance*—every time someone spoke in a conversation. I then used a grounded theory approach (Glaser & Strauss, 1967) to develop a set of qualitative categories, or codes, representing specific design moves and rationale. Table 2 describes each of these codes and provides a brief preliminary example from the data. I coded each utterance in the interview data for these six codes.

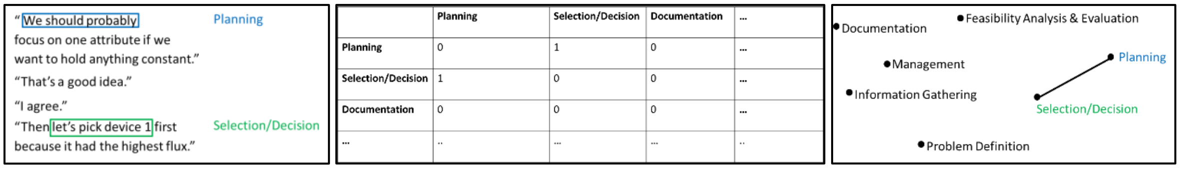
Table 2. Connected Design Rationale coding scheme categories for real-world internship interviews, field notes, and recorded conversations.

Code	**Description**	**Examples**
J.Customer/Consultant Requests	Justifying design choices/devices or strategies by stating that they meet or should meet customer/consultant requests.	*But I guess if they,* ***if the customer requests*** *like a P392 with a this and this and this, then you want to look at the P392 and then use that as a base*
J.Performance Parameters/Requirements	Justifying design choices/devices or strategies by referring to general performance parameters or specific results either from documentation/papers or results from their own testing. The reference to the documentation or performance results does NOT to be explicit.	*So, it's basically like having all the different engineers in our group… and seeing* ***if there is anything that can be tweaked to improve the design or maybe make it more cost effective.***
J.Communication	Justifying design choices/devices or strategies by referring to facilitating communication efforts among colleagues or among engineers and customers.	*Yeah we try to collect as much history so that we have answers* ***so that when we get into the project we have a good understanding of what we're getting into***
M.Experimental Testing	Setting up an experiment by using a control device or have constants and changing one variable at a time. Or using experimental tools or techniques to understand technical features of a product.	*Yeah****, I did [have to do a stress analysis] to a certain extent****… because these lifting I's, they are rated for a vertical 1000 pounds and everything was getting for a 45 degree angle.*
M.Making Design Choices	Choosing a specification or characteristic for a prototype or design product.	***Or we could use propane.***
M.Asking Questions	Asking questions or referring to the move of asking questions	*But the biggest thing is not being afraid to* ***ask the questions.***

EPISTEMIC NETWORK ANALYSIS

To analyze the discourse data, I used epistemic network analysis (ENA) (Arastoopour et al., 2014, 2016; Chesler et al., 2015; Hatfield, 2015; Shaffer et al., 2009, 2016; Siebert-Evenstone et al., 2016; Svarovsky, 2011). Specifically, I used ENA to measure the development of the connections that engineers and interns made between design moves and justifications, as defined by the coding scheme.

ENA measures the connections between discourse elements, or codes, by quantifying the co-occurrence of those elements within a defined *stanza*. Stanzas are collections of utterances such that the utterances within a stanza are assumed to be closely related topically. More specifically, for any two codes, the strength of their association in a network is computed based on the frequency of their co-occurrence in discourse. For example, the stanza in Figure 2a would be coded for planning and selection/decision, but not for documentation, feasibility & evaluation, management, information gathering, or problem definition. Figure 2b shows this stanza represented as a network where the elements that co-occurred in that stanza are now connected while elements that do not co-occur are not connected. Figure 2c shows this stanza as a symmetric adjacency matrix where the codes are represented both as rows and columns. Elements that co-occurred are represented by a one, and elements that did not co-occur are represented by a zero. Not all codes are included in this representation for visual clarity.



“We should probably focus on one attribute if we want to hold anything constant.”
“That’s a good idea.”
“I agree.”
“Then let’s pick device 1 first because it had the highest flux.”

	Planning	Selection/Decision	Documentation	…
Planning	0	1	0	…
Selection/Decision	1	0	0	…
Documentation	0	0	0	…
…	..	…	…	..

Figure 2. (a) Example of a stanza window coded for two codes (b) Example stanza window represented as an adjacency matrix (c) Example stanza window represented as a network

ENA constructs an adjacency matrix for every stanza. The adjacency matrices are summed for every person and sphere-normalized so that people with more discussion are not weighted more heavily than people who have less discussion but still used the same configuration of connections in their discourse.

Finally, the matrices are represented as vectors in a high-dimensional space. Because I identified two groups of interest *a priori* (experts and senior interns), the first dimension in this analysis was determined by a mean-rotation method. This method calculated the mean centroids of the experts and the mean centroids of the interns and used those two mean values to create a line, which defined the mean-rotated dimension (x-axis). The second dimension (y-axis) was calculated by performing a dimensional reduction on the high-dimensional space using singular value decomposition (SVD) to rotate the vectors to show the greatest variance among the matrices. This approach is mathematically similar to a principal components analysis but does not rescale the data. Thus, the second dimension in this analysis is the first dimension in the SVD which accounts for the most amount of variance and is orthogonal to the mean-rotated dimension.

In this rotated space, each person's adjacency matrix is represented as a point in high-dimensional space which roughly corresponds to the network's centroid, or center of mass. The two dimensions in this space can be interpreted by examining the loadings (rotation) matrix, which is similar to the interpretation of the loadings in a principal components analysis. The mean rotation loading matrix is determined by subtracting one group's mean from another for each co-occurrence variable and then normalized to a unit length. The loadings for the remaining dimensions are found using SVD such that all dimensions are mutually orthogonal.

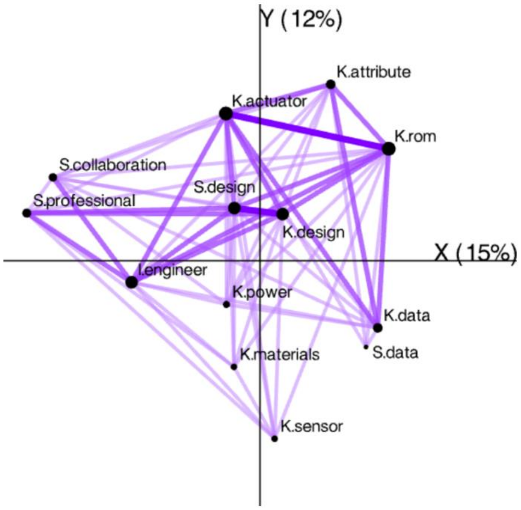
Because ENA examines the co-occurrences of codes, each variable in the loadings matrix represents a pair of codes. This makes the loadings matrix difficult to interpret if there are a large number of codes in the analysis. For example, in this analysis there are 6 codes, which means there are 15 loading vectors, each of which corresponds to a unique co-occurrence of codes. ENA offers a solution to this issue by using an optimization routine to position the original codes in the data in the metric space. The optimization routine minimizes, for any given network, the distance between the centroid of the network graph and the projected point that represents the network under the SVD rotation[3]. Thus, ENA calculates the *node positions* which correspond to both the centroid of the network graph and the projected point. Examining the location of the node positions eases the interpretation of the space while assuring that, given one dimension, the nodes remains fixed for every person's network in that dimension, and thus, each person's network can be compared within an identical, fixed space.

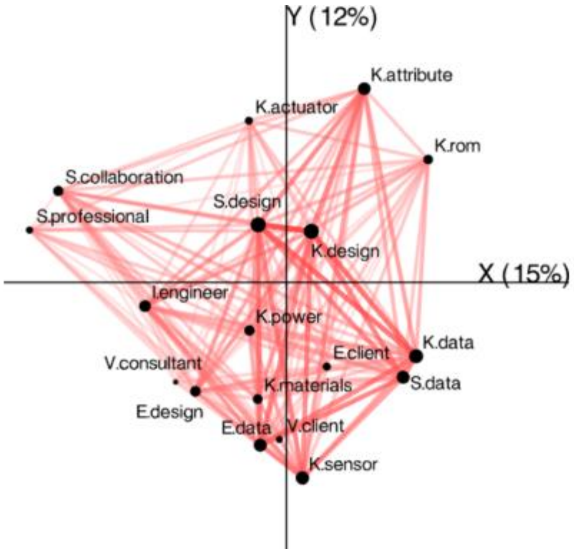
In addition to being represented as a point in high-dimensional space, each person's adjacency matrix is represented as a network of nodes and links. Conclusions can be drawn from examining one person's network, but in many cases, the relevant features become more apparent when one person's network is compared to another's. To compare among different networks, ENA creates a subtracted network representation, which enables identification of the most salient differences between the two networks of interest. To do this, ENA subtracts the weight of each

---

[3] To measure the stress between the centroid and the projected point, ENA computes and reports the strength of correlation between the two using both Pearson's and Spearman's r. The correlations reported are often very high (r > .9) (Shaffer et al., 2016) .

connection in one network from the corresponding weighted connection in the second network. For example, Figure 3a and Figure 3b show the Discourse networks of two first-year undergraduate engineering students (student A and student B) representing the connections the students made while solving a simulated engineering design problem (Shaffer et al., 2016). Figure 3c shows the subtracted network between student A and student B in which the weights of the two networks have been subtracted to obtain one network representation. Purple lines represent connections that were stronger for student A and red lines represent connections that were stronger for student B. Darker, thicker lines indicate larger differences in connection strength and lighter, thinner lines indicate smaller differences in connection strength. Overall, the subtracted network shows that student A had the strongest connections in the upper part of the space and student B had the strongest connections in the lower part of the space.





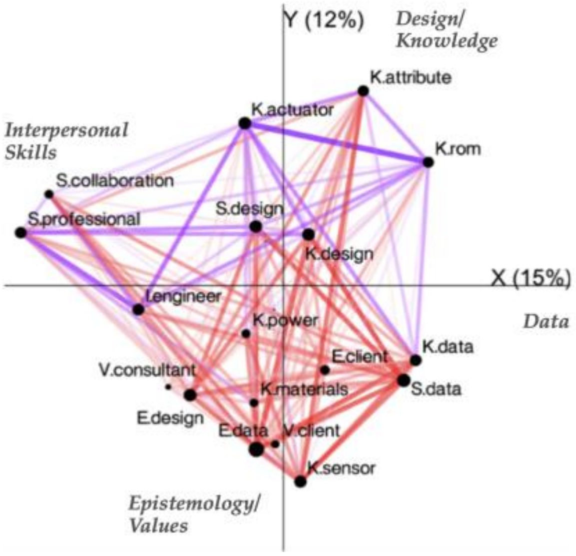


Figure 3. (a) Discourse network of student A (b) Discourse network of student B (c) Subtracted network representation. Figures are from (Shaffer et al., 2016)

RESULTS

The ethnographic examination of the real-world engineering internship focused on six participants: Alice and Bobby (novice interns with 2 months experience at the company), Marcos and Nikos (senior interns with 6 months experience at the company), and Warren and Zara (expert engineers with 15 and 10 years experience at the company, respectively). The results presented are based on my observations and each participant's responses to interviews. The analysis illustrates the patterns of connections novice interns, senior interns, and expert engineers made among moves and rationale.

QUALITATIVE RESULTS

TASKS, PARTICIPANT STRUCTURES, AND PEDAGOGY

The internship program at GammaCorp recruits undergraduate students to work as product engineering interns for eight months. At the start of the program, interns attended an orientation session in which they received information about the company and a training on how to use Creo, a computer aided design (CAD) tool (formerly known as ProEngineering). After the orientation day, interns were required to come to the GammaCorp offices Monday through Friday, 9am to 5pm, and attend team meetings every Monday at 3pm at which all employees, including interns, gave updates about the progress of their tasks.

Throughout the internship program, students received tasks from the coordinator and lead engineer, Warren, who gave them preliminary information to start the task. When assigning tasks, Warren used GammaCorp's Productivity Suite, a project management tool. "I look at a project and say this is easy and so-and-so is really super busy, so I'm going to send it to the intern," Warren explained. "I'm sure if they [the interns] have questions, they will come and ask. And if they don't or if I don't see something in the time that I think I will, then I'll follow up and ask them for status updates."

Warren assigned the interns two categories of tasks: quotes and design work.

QUOTES

The novice interns, Alice and Bobby, were typically assigned quotes. The quote process began when a customer contacted the company to ask for a price estimate on a product. Often, a customer asked for an alteration or a customization to an existing product, which required interns to make changes to existing forms or complete several different forms for one quote.

For example, when I asked Alice about one of her quotes, she explained she was working on "a pneumatic torque wrench, custom, with a hexagon adapter." The customer had contacted GammaCorp to ask for a price estimate and specifications for the torque wrench and this information was forwarded to Alice.

The customer had two customized requests: (1) that specialized parts should be added to the torque wrench such that it was compatible with Caterpillar machines and (2) that the tool have a Caterpillar decal. Alice explained the parts: "They are all components of the prototype… that's the wrench, this is the adjustable action arm, this is the cassette, and this is the adaptor."

Before she created a form for the customized parts, she first had to identify an uncustomized torque wrench by looking "at each one of the descriptors [of the wrenches in the inventory] and clicking "on the one that seemed similar" from the current inventory to use as a model the customized wrench.

As a result, Alice had to use three different order forms for this one quote: one form for the uncustomized torque wrench, one form for the added specialized parts, and one form for the decal placed on the tool.

Thus, at GammaCorp, quotes were a task assigned to interns in which they provided price and specification information for a customer's requested product. In the example above, Alice completed a quote for a customer who requested a customized torque wrench tool. Most of the customized quotes required making changes to existing forms or completing multiple forms. In this case, Alice had to complete three separate forms for one product quote.

DESIGN WORK

The senior interns, Marcos and Nikos, were typically assigned design work that took place after a customer received a quote and placed an official order for a product. After the customer placed an order, interns designed the product using Creo, the CAD tool. Once the product was designed and approved, interns sent the specifications to manufacturing for production.

For example, Marcos was assigned a task to design a hydraulic cylinder with customized handles, which were called clevises. When he received the task, the cylinder had already been quoted and the customer had placed an order.

Marcos met with Warren, his supervisor, to receive more information about the design task. During the meeting, Warren told Marcos that he needed "a couple clevises [handles], a lock nut, and an extended plunger." Marcos explained that he and Warren "drew up some sketches and [Warren] said you can do it. I was like yeah sure, I'll go put it together."

Marcos spent a week creating preliminary drawings using Creo. He explained that the hydraulic cylinder "can lift things or push something and they [the customer] wanted a clevis, which is like a handle on one side and a handle on the side that was coming out, whatever it was going to be pulling."

After searching the company's product database, Marcos realized, "these clevises were already made in Creo." He further explained, "I didn't know that at first… Once I figured out they were made, I just had to make an adapter and figure out how to put them on the actual cylinder."

After receiving feedback from other engineers on his drawings, Marcos met with Warren again to finalize the design and have it approved. Then, Marcos then completed the documentation, and the product was sent out manufacturing.

Marcos concluded, "It ended up being shipped out to the customer."

Thus, at GammaCorp, design work was a task assigned to interns in which they designed a product based on a completed quote. In the example above, Marcos was assigned a design task in which he needed to design clevises (handles) for a hydraulic cylinder. He used Creo, the CAD tool, to design and sketch the handles, completed the customizations, and met with Warren for approval of the design. The final task in design work was to send the specifications to manufacturing so that product could be built and sent to the customer.

For both quotes and design work tasks at GammaCorp, the process was organized through one key pedagogical method: *The informal feedback cycle*.

INFORMAL FEEDBACK CYCLE (IFC)

The informal feedback cycle (IFC) (Figure 4) was the main pedagogical method at GammaCorp. It consisted of two forms of participant structures: individual desk work and group meetings. Individual participant structures consisted of interns working individually at their desks and group structures consisted of interns and engineers working together on a task either at an engineer’s desk or an intern’s desk. Both individual and group participant structures existed at various points in the IFC.

The first step of the IFC was *Getting Stuck*, meaning the intern was unsure of what to do next and could not make progress on the task. Getting stuck was an individual participant structure in which the intern worked individually at their desk on a quote or design task.

After realizing she was stuck, the intern would initiate an informal meeting with an engineer (or a more senior intern) and would begin the second step of the IFC: *Discussion of Work*, which was a group participant structure. In this step, the engineer would ask the intern clarifying questions about the task and gather information on what the intern had completed thus far.

When the engineer had enough information, he would initiate the third step of the IFC: *Reflection-On-Action*, which was a group participant structure. At this point, the engineer reflected with the intern on her work, which would involve thinking out loud through the task with the intern, partially working through the task with the intern, providing models of work that was similar to the task at hand, providing feedback on the work, and suggesting next steps.

Typically, the reflection-on-action session ended once an intern determined that she had enough information to continue the task. This began the fourth step of the IFC: *Getting Unstuck.* The intern would then return to their desk to continue working on the task and engage in an individual participant structure. If she had more difficulty and got stuck again on the same task, the intern would initiate another informal meeting and the cycle would continue until the task was completed and approved by the supervisor.

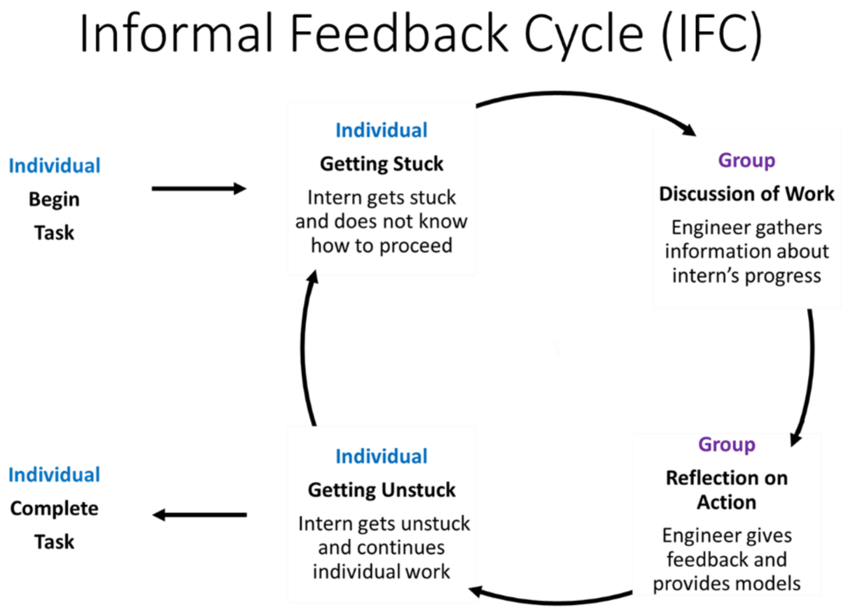


Figure 4. Informal Feedback Cycle (IFC) was the pedagogical approach for each task. Interns applied the IFC was applied to both quotes and design work. The IFC incorporated two forms of participant structures: individual and group.

Individual: Getting Stuck

The IFC began when the intern, working individually on the task at their desk, would get stuck. In the quote example above, Alice was working on the pneumatic torque wrench quote at her desk. After a few minutes, she messaged a senior intern, Marcos, for assistance because she "didn't know what to do next."

After a few seconds, Marcos arrived at Alice's desk. She pointed at her computer screen and explained, "Where did those product numbers come from? I've never seen them."

Marcos replied “These are CAT [Caterpillar] product numbers… But I don’t know if that’s what you should do for CAT though.” So, Marcos suggested that they ask an engineer, Zara, for guidance on what to do next.

GROUP: DISCUSSION OF WORK

The second step of the IFC, Discussion of Work, began when Marcos and Alice approached Zara’s desk and asked for help on the quote.

When the meeting started, Zara began to gather information about Alice’s progress on the quote. Zara accessed the quote on her computer and reviewed the information.

She let out a sigh: “Ugh. Marcos what are you doing to her?”

Marcos responded, “I don’t know. That’s the thing. That’s why we have questions… I did it because I thought he was releasing the M numbers in our system.”

Zara asked, “Have you done a form 202?”

Alice responded, “Uh yes. I’ve done them for production support. So, it’s a little different, right?”

GROUP: REFLECTION ON ACTION

Zara explained, “Yes, this is different. You will actually have to split this into two forms: M numbers and CAT numbers.”

Alice asked, “What’s different about it?”

Zara responded, “I’ll show you.” As she navigated the form on the computer, she explained that the process required “a separate workflow… Basically what that means is anytime you’re reinstating something, anytime you’re coding, you use this because you don’t actually do the stuff in [company tool].”

Alice asked, “What about the coding?”

Zara responded, “Well, let’s see what it’s similar to… Looks like it’s a W 4000. So that part is right. It’s going to be a W series.”

After Zara obtained the part number, she gave Alice the part number and showed her where to enter the information in the form.

Here, Zara and Alice participated in reflection-on-action, the third step of the IFC. Zara first criticized Alice and Marco’s approach to the problem and then explained why the approach was problematic: “I’ll show you… [it’s] a separate workflow.” Then, after some reflection on the task, Zara suggested a product code. Thus, the reflection-on-action occurred as Zara worked through the task with Alice, provided models of quote forms, and explained how Alice should proceed with the quote.

INDIVIDUAL: GETTING UNSTUCK AND THEN STUCK AGAIN

At this point, Alice determined she was unstuck and thus, went back to her desk to continue working on the quote individually.

Two hours later, Alice got stuck again and initiated a second iteration of the IFC. She messaged Marcos for help and asked, “Are we buying one or five? Jerry [an engineer] said we’ll buy five to have the price, but earlier I heard twenty.”

Marcos suggested they meet with Jerry to clarify.

GROUP: SECOND ITERATION OF DISCUSSION OF WORK AND REFLECTION-ON-ACTION

Alice and Marcos went over to Jerry's desk and asked for the quantity information. Jerry explained that because this quote was for a pneumatic wrench tool, "this was a five-piece minimum."

Alice asked, "Okay so then we do the coding for the M numbers and then do the CAT numbers?"

Jerry clarified, "No… Were there CAT numbers pulled for this?" Alice and Marcos said yes, and Jerry replied, "No, no, so the way they're buying it is through an indirect system, so they can't buy it as a CAT system right now."

Alice asked, "So this part [points at screen] should be M numbers and the CAT numbers we can do later."

Jerry replied, "Correct. Down the road, there might be more changes... Okay you got it figured out?"

Alice said, "Yup, thank you," and walked back to her desk.

IFC DESIGN WORK EXAMPLE

In this section, I briefly revisit the Marco's design work example from above. When he received the design task, Marcos "had no idea what the heck was going on." He was stuck and thus, initiated a meeting with his supervisor, Warren.

During the meeting, Warren reflected on the task with Marcos: he explained the requirements of the design and they "drew up some sketches." After the meeting, Marcos went back to his desk to continue working on the task.

Then, when he got stuck again, Marcos approached another engineer for more feedback on his work. He continued working on the design until it was approved by Warren and sent to manufacturing.

IFC: THE PEDAGOGICAL KEY TO SOLVING ILL-STRUCTURED PROBLEMS

In sum, the IFC was a key pedagogical structure for interns completing quotes and design work. When interns were assigned a task, they received minimal direction. As a result, interns were often stuck and unsure what to do, such as when Marcos received his design task and had “no idea what the heck was going on.”

To get unstuck, interns would initiate an informal meeting with an engineer (or a more senior intern). The engineer would then ask clarifying questions about the task and what the intern had completed thus far. When the engineer had enough information, he or she would provide feedback to the intern, which would involve suggesting next steps, providing models of work that was similar to the task at hand, and partially working through the task with the intern. For example, when Marcos met with Warren, they “drew up some sketches” together, and Warren clarified some of the projects tasks.

Typically, the reflection-on-action session ended once an intern determined that they had enough information to continue the task. Occasionally, the session ended for alternative reasons such as the engineer had limited time or there was an interruption in the meeting. Either way, after the meeting concluded, the intern would return to their desk and continue working on the task individually. If she had more difficulty, the intern would initiate another informal meeting, and the feedback cycle would continue until the task was completed and approved by the supervisor.

Both Alice and Marcos relied on the IFC when completing their tasks because they received tasks in which explicit procedures did not exist and instead, procedures had to be invented along the way with the guidance of more experienced mentors. For example, when Alice approached Zara for help on the quote, Zara reflected on the task and realized the task was unlike the other quotes that have been completed before: “This is different. You will actually have to split this into two forms: M numbers and CAT numbers.”

In addition, Zara thought aloud as she worked through with Alice on the quote: “Well, let’s see what it’s similar to… Looks like it’s a W 4000. So that part is right. It’s going to be a W series.” She and Alice determined what the next steps would be as they worked through the task together.

Similarly, in the design work example, Marcos and Warren worked through the task together in their meeting. They “drew up some sketches” to determine how to create and attach clevises onto a cylinder. After the meeting, while individually working on the cylinder, Marcos described the task as “more of an experience thing… there is no set rules on how to quote or design something.”

In other words, quotes and design work possess multiple solution paths and have an inherent uncertainty about them. Both require learners to make judgements about the task and to determine the necessary procedures along the way. Thus, both Alice and Marcos relied on the IFC because both quotes and design work were ill-structured tasks—problems that cannot be solved using predefined methods and have emerging, unanticipated consequences.

NOVICE INTERNS: ALICE

Because the IFC structure was the main pedagogical approach for ill-structured problems at GammaCorp, I use the IFC configuration to organize the remainder of the analyses in Part One.

In this section, triangulating both field notes and interview data, I closely follow two iterations of the IFC of one novice intern, Alice, while she worked on an ill-structured quote task. For each iteration of the IFC, I examined her moves, rationale, and connections among moves and rationale.

IFC: First Iteration

During the first month of her internship, Alice was asked to complete a quote for a hydraulic cylinder.

I observed Alice sitting at her desk working on the quote. After twenty minutes, Alice was stuck, so she made a design move: she asked an engineer, Zara, for help. She walked over to Zara's desk and asked, "Can you help me on this quote?"

After accessing the quote information on the computer, Zara replied that the quote was a customized product. She opened an example of a customized product and explained the next steps that Alice should take: "The only thing that's going to be different is a different Bill of Materials… so you'll always use US custom products, non-purchased…. And you'll have to fill in the product coding and all that other stuff."

Alice nodded her head and made another move by asking, "I'll get started on it and finish it up and can you check over it for me?"

Zara said yes and added that she could walk Alice through whichever aspects of the quote she still needed help with. Alice went back to her desk to continue working on the quote.

IFC: Second Iteration

Fifteen minutes later, Alice was stuck again and initiated another meeting with Zara.

Alice gave Zara the quote ID number again, and Zara located the file on the computer. After silently reviewing the information, Zara asked, “Did you create a new form for this one yet?”

Alice explained that she didn’t know how to do that, so Zara showed Alice how to enter the correct information on the forms.

Zara paused for a few seconds then said, “I’m going to show you something. Because this is so different from anything that we usually have, it’s not standard… I’m going to show you an example of one that Warren did [that is like the one we are doing].” After opening Warren’s quote to use as an example, Zara explained to Alice the similarities between the current quote and Warren’s quote.

Alice nodded through the explanation, and then confirmed her next steps by making another move which was asking another question: “Okay, so I fill this out, send it to custom products and then, I dig up all these prints for the cylinder?” Zara nodded her head, and Alice asked, “You said the plunger and the base and all the mounting were…?”

Zara answered Alice’s question and provided an explanation, “Yes, the plunger and base are all custom because of the way they mount to the steel structure itself. Otherwise, they are pretty much a standard cylinder.”

Alice made another move by asking one final question: “So I won’t have to do any bearings or seals or anything?”

Zara answered, “No those are pretty much standard. It’s basically just a standard RR 1506 with modifications to adapt it to the steel plate.”

Alice replied, “Okay that makes sense,” and went back to her desk to continue her work.

ANALYSIS: ALICE'S MOVES AND RATIONALE

When receiving help from Zara during the informal feedback cycle, Alice's main move was to ask questions:

> "Can you help me on this quote Zara?"
>
> "I'll get started on it and finish it up and can you check over it for me?"
>
> "Okay, so I fill this out, send it to custom products and then, I dig up all these prints for the cylinder?"
>
> "You said the plunger and the base and all the mounting were…?"
>
> "So, I won't have to do any bearings or seals or anything?"

When I interviewed Alice, I asked her how she proceeded when she received her first few quotes. She replied, "I asked Kyler."

When I asked her to explain further, she said, "I usually go to Kyler first because he's another intern… But I feel kind of nervous going to other engineers so far." Although she reported that she felt nervous, Alice had asked other engineers for help before, as shown above when Alice approached Zara for assistance on the hydraulic cylinder quote. Alice admitted that "when Kyler leaves [in one month], I'll probably be asking them [engineers] more questions all the time."

As shown above, Alice only made the move of asking questions in her discussions with Zara and did not provide any rationale this move. Likewise, in her interview responses, Alice claimed that asking questions was one of her main moves. Thus, Alice, a novice intern, did not connect the move of asking questions to other moves or connect the move of asking questions to any rationale, and thus did not make any connections among moves or rationale.

SENIOR INTERNS: NIKOS

Once again using the IFC to structure the analysis, in this section I triangulate field notes and interview data and closely follow three cycles of the IFC of one senior intern, Nikos, while he worked on an ill-structured design task. For each iteration of the IFC, I examined his moves, rationale, and connections among moves and rationale.

IFC: FIRST ITERATION

Midway through the program, Nikos was assigned a task to design a customized product for a customer—a tow cart that would house a variety of tools. Nikos received the quote and the customer's requests which gave him an approximate budget and some direction on which parts to use to design the cart.

When Nikos received this information, he said in his interviews that his initial reaction was, "Hey, I've never seen anything like this before, what's the first thing I should do?"

So, he made a move and approached his supervisor, Warren, to receive guidance on what his first steps should be.

Warren explained that Nikos had to find a way to design the cart using Creo, the CAD drawing tool. Warren suggested that instead of trying to design the final product, Nikos should first "have the really basic design done before getting into too many specifics" trying to meet the as many of the customer's requests as possible. Nikos could then then "complete several reviews" to receive feedback on his work and iterate through his designs. During their meeting, Warren and Nikos made design moves by working together on sketching some basic designs.

Warren asked Nikos, “Can you do it?”

Nikos replied “Yeah, sure I’ll go put it together.”

When Nikos returned to his desk to work on designing the tow cart, he began by reviewing the sketches that he and Warren had made. When I interviewed Nikos about the work he did on this first design iteration, he explained, “I kind of had a basic idea in my mind of what I wanted to do. So, I wanted to model it up in Creo… to show it to everybody.”

After making moves by experimenting with Creo, Nikos figured out which pieces he could mount together and how they would fit collectively.

IFC: SECOND ITERATION

One week later, Nikos had a preliminary design, as Warren had suggested. Nikos made more moves by printing out the drawings and asking a group of engineers for feedback.

Unfortunately, it did not go as well as he had expected. “They railed me on everything,” Nikos laughed as he recalled the meeting.

For example, he had some hoses sticking out in many different places on the tow cart, which blocked the customer’s access to the controls on the cart. In the meeting, Warren reminded Nikos to focus on the customer requests and said, “They [the customer] need to be able to reach these full controls… and be able to operate everything on this tow cart standing from one point.”

The engineers asked that Nikos make several changes and present the design to them once the changes had been made.

IFC: THIRD ITERATION

Several days later, Nikos completed a revised design. When I interviewed him about the moves he made on this second design iteration, he explained that he conducted experimental and technical analysis on the steel I-beams for the towcart. He said, “I did [have to do a stress analysis] to a certain extent… because these lifting I-beams are rated for a vertical 1000 pounds and a 45-degree angle. So, I had to make sure [it wouldn’t fail].”

When he had a design prepared, Nikos met with the engineers a second time and this time they asked him to make only minor design changes and complete the documentation for the product.

To complete the documentation, Nikos made a move of completing a part release form that released all the parts into the manufacturing system. When I interviewed him, Nikos explained the rationale behind documentation, “Basically anytime that we have anything new that is designed… we need to release a new part into the system with all the correct coding, cost information… so that orders can be made.”

After the product was assembled, Nikos made further design moves by going to the manufacturing area to take photos of the product. His rationale was that he wanted to “take pictures of the changes” so other engineers could see a final version of the product or “so if in the future someone [a customer] wanted to make future orders of these, they could see what it looked like.”

Fortunately, when Nikos went down to the assembly line, the product was assembled properly and ready to be shipped off to the customer. Nikos concluded in the interview, “Apparently, they didn’t have any problems. Put them in boxes and were ready to be shipped when I finally came down and was notified they were being built. So, it was like okay, that's done.”

ANALYSIS: NIKOS’ MOVES AND RATIONALE

This extended example shows how Nikos engaged in design work to design a product for a customer. Unlike Alice, the novice intern, who only made the move of asking questions, Nikos made several other moves and connected these moves to rationale, mostly focusing on the justification of communication.

For example, in his first design iteration, Nikos met with Warren and then went back to his desk to review the initial sketches they made together. When I interviewed him about his work, Nikos said “I kind of had a basic idea in my mind of what I wanted to do. So, I wanted to model it up in Creo… to show it to everybody.”

Here, Nikos connected the *move of making a design decision*: “I kind of had a basic idea in my mind of what I wanted to do. So, I wanted to model it up in Creo” *in order to communicate* with the other engineers: “to show it to everybody.”

After receiving feedback from the engineers, Nikos continued his design work. In an interview, he explained that in his third design iteration, he “did [have to do a stress analysis] to a certain extent… because these lifting I-beams are rated for a vertical 1000 pounds and a 45-degree angle. So, I had to make sure [it wouldn’t fail].”

Here, Nikos connected *the move of experimental/technical testing*, “I did [have to do a stress analysis] to a certain extent” to the *rationale of performance requirements*, “because these lifting I-beams are rated for a vertical 1000 pounds and a 45-degree angle.”

Finally, when documenting his design procedures, Nikos made one last connection. He wanted to “take pictures of the changes… so if in the future someone [a customer] wanted to make future orders of these, they could see what it looked like.”

Here, Nikos connected the *move of making a design decision*: “take pictures of the changes” *in order to facilitate communication* with customers: “so if in the future someone [a customer] wanted to make future orders of these.”

Thus, the results from his interactions with Warren in the IFC during the design process and his interview data about the documentation process indicate that Nikos made a few connections among moves and rationale. He connected the move of experimental testing with the rationale of performance parameters, but more often he connected the move of making design decisions to the rationale of facilitating communication with customers or other engineers.

EXPERT ENGINEERS

In this third analysis, I focus on the connections that experts made among moves and rationale. However, because the data collection centered on interactions between mentors and interns, I did not observe experts working with other experts on design problems. Thus, in this section, I revisit both Alice’s quote example and Nikos’s design work example and focus on how the expert engineers, Zara and Warren, interacted with interns in the IFC.

ZARA AND ALICE’S IFC GROUP INTERACTIONS

In the first example that I revisit, Zara, the expert engineer, worked on a quote for a hydraulic cylinder with Alice, the novice intern. When working together, Zara used a previously completed quote as a model for Alice and explained the rationale warranting the moves of using specific quote forms: “Because this is so different from anything that we usually have, it’s not standard… I’m going to show you an example of one that Warren [another engineer] did.”

When Alice asked a question about the plunger and base of the product, Zara explained that Alice would have to use a custom form for those two parts: “the plunger and base are all custom… otherwise they are pretty much a standard cylinder,” and she provided a rationale based on the performance and design of the product: “because of the way they mount to the steel structure itself.”

ANALYSIS: ZARA’S MOVES AND RATIONALE

When working with Alice, Zara made connections among various moves and rationale. First, Zara answered Alice’s question about the plunger and base, “Yes, the plunger and base are all custom because of the way they mount to the steel structure itself. Otherwise, they are pretty much a standard cylinder.”

Here, Zara connected the *move of making design choices*: “Yes, the plunger and base are all custom” *based on performance parameters* of the product: “because of the way they mount to the steel structure itself.”

When I interviewed Zara about her interactions with Alice, she discussed the importance of the move of asking questions: “The thing is being confident in your abilities and being comfortable with asking questions because engineering is not necessarily about knowing the answers… [it’s about] being able to figure out or verify that they're going to provide what the customer is actually looking.”

In this excerpt, Zara connected the *move of asking questions*: “The thing is… being comfortable with asking questions” *in order to clarify the customer’s requests*: “…to figure out or verify that they're going to provide what the customer is actually looking for.”

Thus, Zara made more of a variety of connections among moves and rationale than the interns made. Like the interns, Zara included the move of asking questions and the rationale of communication, but she also incorporated justifying design moves based on customer requests and the performance of the product.

WARREN AND MARCOS’S IFC GROUP INTERACTIONS

In the second example that I revisit, Warren guided Nikos through the design task of a tow cart.

When Nikos met with Warren to receive guidance on this tow cart design, Warren explained that Nikos had to design the cart using Creo, the CAD drawing tool. Warren suggested that instead of trying to design the final product, Nikos should first “have the really basic design done before getting into too many specifics.”

Once Nikos had a preliminary design, Warren and other engineers met with Nikos to provide more detailed feedback on the design. After reviewing Nikos’s design, Warren identified some issues.

Warren explained that “they [the customer] want this design pump… with all these full controls and… they want storage for these hoses. And they want to be able to lift and drive it around the shipyard." However, in Nikos's design, the orientation of the pump resulted in "all these hoses are sticking out in different ways," which blocked the customer's access to the controls on the cart. Thus, the design did not meet some of the performance requirements or customer requests.

ANALYSIS: WARREN MOVES AND RATIONALE

When working with Nikos, Warren made connections among various moves and rationale. First, Warren and other engineers met with the intern to provide feedback on the design work. Warren summarized the performance parameters and the customer requests for Nikos: "They [the customer] want this design pump oriented in a certain way with all these full controls and… they want storage for these hoses. And they want to be able to lift and drive it around the shipyard."

Here, Warren connected the *move of making design decisions*: "the pump had to be oriented a certain way" *based on the customer requests*: "to have the customer operate everything on this tow cart standing from one point."

When I interviewed Warren about giving feedback to the interns on their design projects, he explained, "We [need to] ask, what is the application? What is the customer looking for? And then look to make sure the design meets those requirements... Be it building tooling or something for the production line."

Here, Warren connected the *move of making design decisions*: "Be it building tooling or something for the production line" to the *rationale of customer requests*: "What is the customer looking for?" and to the *rationale of performance parameters*: "Look to make sure the design meets those requirements."

Warren continued to explain that successful interns at GammaCorp asked many questions. He said, “It [asking questions] kind of makes them [the interns] step back and rethink that they need to explain or reiterate: here's what I understand you're looking for.” It was important to ask questions and have effective communication so that interns didn’t, as Warren put it, “spend all that time and effort on something that's not needed or wanted.”

In this excerpt, Warren connected *the move of asking questions*: “It [asking questions] kind of makes them [the interns] step back and rethink…” to the *rationale of effective communication*: “they need to explain or reiterate: here's what I understand you're looking for.”

Thus, Warren made more of a variety of connections among moves and rationale than the interns made. Like the interns, Warren included the move of asking questions and the rationale of communication, but he also incorporated justifying design moves based on customer requests and the performance of the product.

SUMMARY

In sum, the novice intern, the senior intern, and the expert engineers all had different patterns of connections among moves and rationale. The novice intern, Alice, mainly made the move of asking questions and made no connections among moves and rationale. The senior intern, Nikos, made connections, but he mainly connected design moves to the rationale of communication and had few connections to other sources of rationale. In contrast, both Warren and Zara made a variety of connections among moves and rationale and incorporated various forms of rationale. Such connections included asking questions in order to have effective communication, making design decisions based on the performance of the product, and making design decisions based on customer requests.

QUANTITATIVE RESULTS

The qualitative investigation above reveals an in-depth examination of the pedagogical methods and participant structures among interns and engineers. However, when examining connections, the number of interactions among elements rises exponentially, and thus a qualitative analysis can become difficult to conduct and critical findings may be overlooked. A solution to this issue is to employ a quantitative investigation using Epistemic Network Analysis (ENA) which allows for measuring connections among elements in coded data and representing such connections as dynamic network models. ENA measures the strength of association among connected elements over time and enables a direct comparison of networks visually and also by using summary statistics.

In this analysis, I used ENA to create discourse networks based on the interview data from two novice interns, two senior interns, and two expert engineers in which connections are modeled as co-occurring codes within a single interview utterance.

NETWORK ANALYSIS

Figure 5 shows the discourse networks for Alice and Bobby, the two novice interns. As demonstrated by the qualitative analysis above, both Alice and Bobby did not make connections among design moves and rationale. Thus, the network representations are blank because there are no links among moves and rationale.

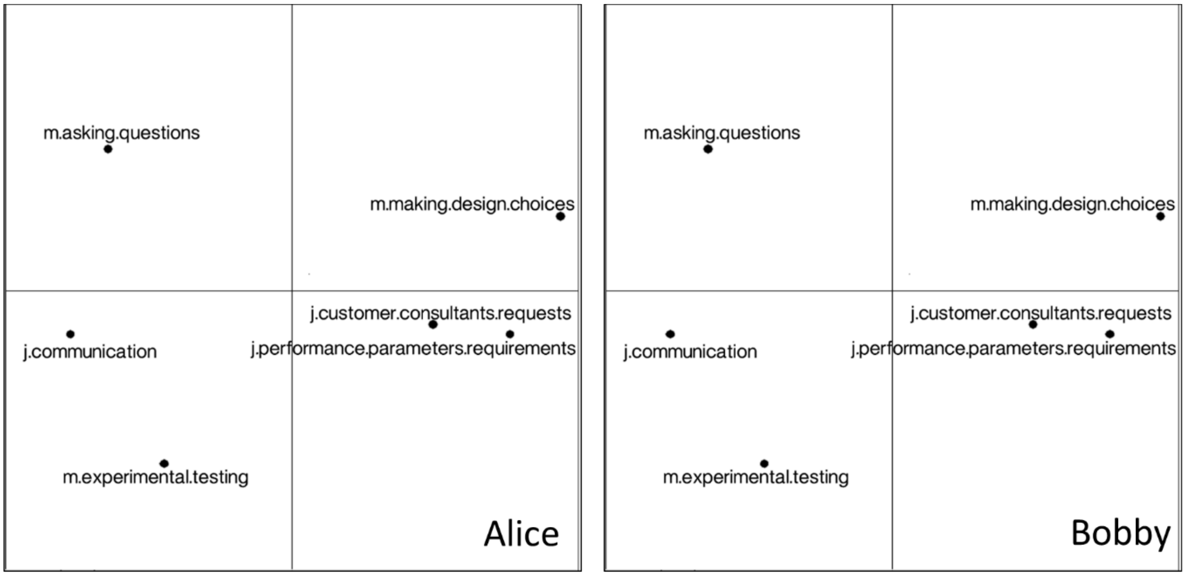


Figure 5. Discourse networks for the two novice interns, Alice (left) and Bobby (right). The absence of links indicates that there are no connections among moves and rationale.

Figure 6 shows the discourse networks for Marcos and Nikos, the two senior interns. These networks model show the structure of connections among design moves and rationale. The networks are weighted, meaning that connections that were made more frequently are represented by darker, thicker lines (stronger connections) and connections that were made less often are represented by lighter, thinner lines (weaker connections). In both networks, the strongest connections were between the move of asking questions and the justification of communication. Marcos had an additional strong connection between the move of making design choices and the justification of communication. Thus, the most salient connections that the senior interns made were linked to the justification of communication, which was also shown by Nikos's qualitative analysis.

Although Marcos and Nikos both had strong connections to the justification of communication, their networks had some slight differences in patterns of connections. For example, Nikos's network showed connections to the move of experimental testing, while Marcos does not make any connections to experimental testing. In contrast, Marcos had a connection between asking questions and making design choices, while Nikos lacked this connection. However, overall Nikos and Marcos had similar patterns of connections.

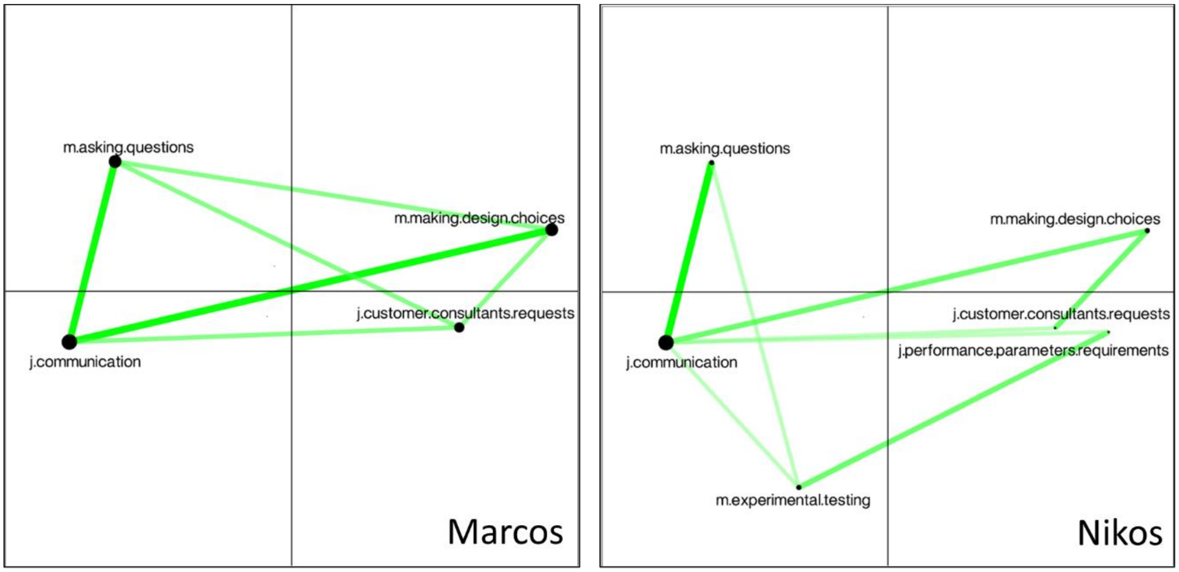


Figure 6. Discourse networks for the two senior interns, Marcos (left) and Nikos (right). Thicker lines represent stronger connections and thinner lines represent weaker connections.

In addition to having similar patterns of connections, Marcos and Nikos also had a similar number of connections to moves and rationale overall. Marcos had six connections in his network and Nikos had eight connections. If we also consider the weights of links, we can calculate a weighted density, which summarizes the number of connections with respect to the weights of the links. The weighted density of Marcos's network was .15 and the weighted density of Nikos's network was .17.

In contrast, the two expert engineers had denser networks than the interns (Figure 7). Zara had thirteen different connections among moves and rationale and Warren had fourteen different connections among moves and rationale. The weighted density of Zara's network was .20 and the weighted density of Warren's network was .24, which was higher than both senior intern weighted densities.

More important than the number of links among moves and rationale are the different patterns of connections that the experts had in their network. Like the interns' networks, the experts had strong connections to the justification of communication, but they also had strong connections to other elements that the interns were lacking in their networks. Zara's strong connections were between asking questions and justifications based on the customer and asking questions and making design choices. And Warren's strong connection was between making design choices and justifications based on the customer.

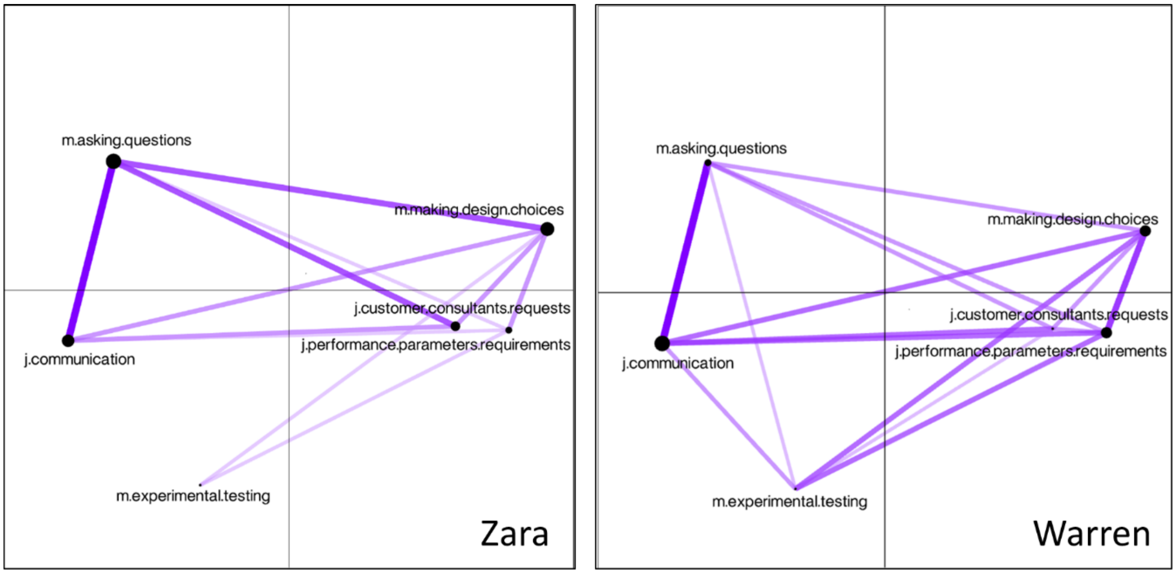


Figure 7. Discourse networks for the two expert engineers, Zara (left) and Warren (right). Thicker lines represent stronger connections and thinner lines represent weaker connections.

To directly compare the senior intern networks to the expert engineer networks, I created a mean network representation of the senior interns and of the expert engineers (Figure 8). This representation averages the weights of the links for each group of interest.

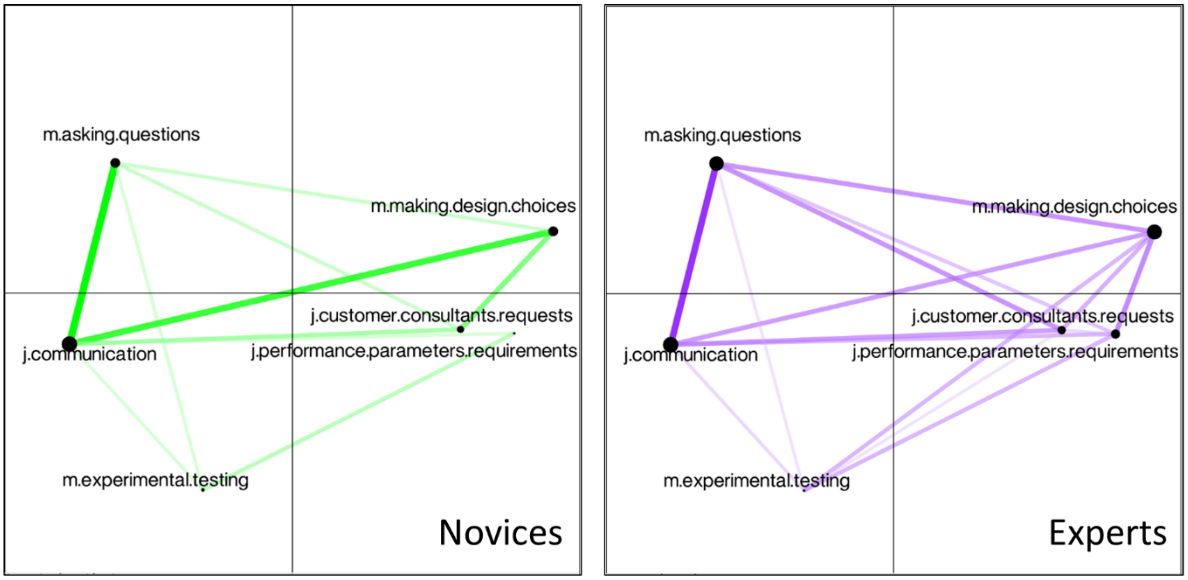


Figure 8. Mean network representations of senior interns (left) and expert engineers (right). This is average of the network weights for each group.

To more clearly compare the senior intern and expert engineer networks, I created a subtracted network, which enables identification of the most salient differences between the two networks of interest (Figure 9). The subtracted network reveals that experts made more connections among a variety of moves and rationale than novices. Upon a closer investigation, the subtracted network shows novices had connections to only one type of rationale: communication. In contrast, experts exhibited connections to all three forms of rationale: the rationale of communication, as well as rationale based on the customer requests and rationale based on performance parameters. In addition, unlike the novices, experts also made connections *between* two justifications, indicating that at times, they provided multiple forms of rationale in one utterance. Thus, as shown in both the quantitative network analysis and the qualitative analysis above, experts provided a variety of rationale for their moves, provided multiple forms of rationale at one time, and in turn, had more sophisticated reasoning than the novices.

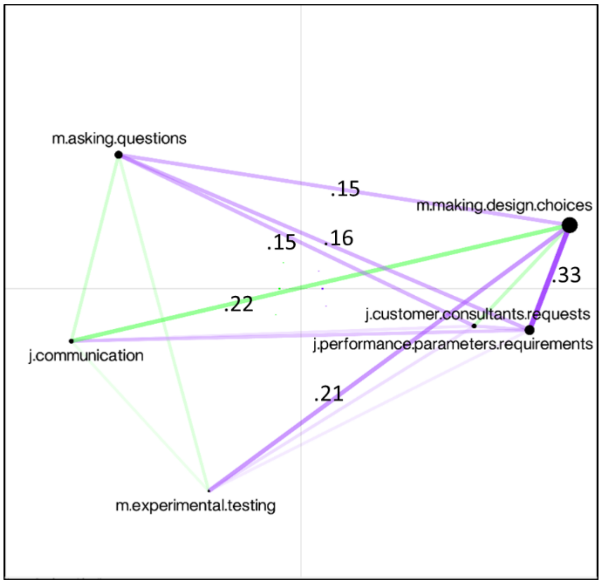


Figure 9. A subtracted network comparison between expert engineer and senior intern discourse networks. This representation is the result of the difference in weights between the mean expert network and the mean intern network. The largest six differences in terms of weights are shown.

CENTROID ANALYSIS

In addition to the network representations, ENA creates a metric space which shows differences between the locations of expert and novice centroids. As explained in the methods, a centroid analysis is advantageous when comparing a number of different networks simultaneously. Clearly, examining centroids is not particularly relevant in Part One of this study due to the small sample size of expert engineers and interns. However, I examine centroids in the ENA space here because in subsequent analyses in Part Two and Part Three, I examine a larger sample size using virtual internship data and will use the same metric space shown here in Part One.

This section examines the centroids of the two senior interns and the two expert engineers shown altogether in one two-dimensional plot (Figure 10). The first dimension in this plot (the x-axis) was calculated using a mean-rotation and the second dimension (the y-axis) is the first component of the SVD rotation, such that it is orthogonal to the mean-rotated dimension.

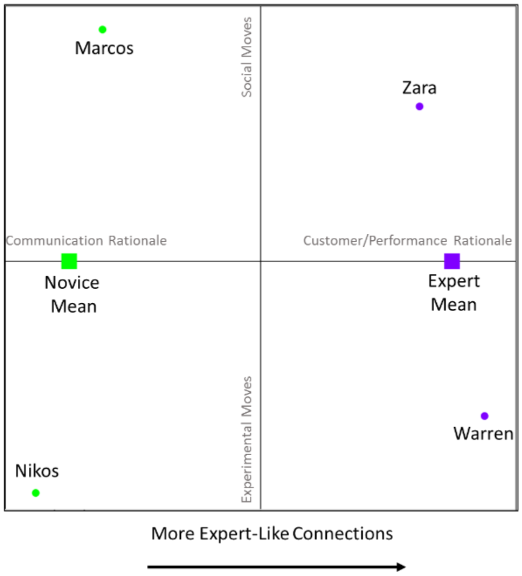


Figure 10. Centroids of two senior interns (green circles; Marcos and Nikos) and of two expert engineers (purple circles; Zara and Warren) plotted in a metric space created from a mean rotation which plots the mean centroids of each group (green and purple squares) and maximizes the variance between these two groups. The x-axis differentiates between experts and novices, and the y-axis differentiates within experts and novices.

The mean-rotated dimension (x-axis) accounted for 48% of the variance and the SVD dimension (y-axis) accounted for 45% of the variance. The dimensions can be interpreted by examining the loadings that are greater than the absolute value of .25 (Table 3).

The top five items that loaded positively on the mean-rotated dimension (positive x-axis) were (1) making design choices based on the design's performance parameters, (2) making design choices and conducting experimental tests, (3) asking questions because of the performance parameters, (4) asking questions because of the customer requests, and (5) asking questions and making design choices. The one item that loaded negatively on the mean-rotated dimension was making design choices based on communication efficiency. Thus, this first dimension on the x-axis can be interpreted as the customer/performance rationale (positive x-axis) vs. communication rationale (negative x-axis) dimension. As Figure 10 shows, expert networks were plotted on the positive x-axis indicating that experts focused more on the design's performance parameters and customer's requests and less on rationale based on communication, as was shown in both the network and the qualitative analysis.

Table 3. Loadings from mean-rotated dimension (x-axis) in real-world internship metric space with values greater than the absolute value of .25.

MEAN ROTATED DIMENSION (X-AXIS) LOADINGS MATRIX	
Connection	**Loading Value**
M.Making Design Choices & **J.Performance Parameters/Requirements**	+.58
M.Making Design Choices & M.Experimental Testing	+.37
M.Asking Questions & **J.Performance Parameters/Requirements**	+.29
M.Asking Questions & **J.Customer/Consultant Requests**	+.27
M.Asking Questions & M.Making Design Choices	+.27
J.Communication & M.Making Design Choices	- .38

The top two items that loaded positively on the SVD dimension (positive y-axis) were (1) asking questions and making design choices and (2) asking questions because of customer requests. The top two items that loaded negatively on the SVD dimension (negative y-axis) were (1) experimental testing because of the performance parameters and (2) experimental testing in order to communicate more effectively. Thus, this second dimension on the y-axis can be interpreted as the social (positive y-axis) vs. technical (negative y-axis) dimension. This dimension reveals differences within experts and within novices.

Table 4. Loadings from singular value decomposition (svd) dimension (y-axis) in real-world internship metric space with values greater than the absolute value of .25.

SVD DIMENSION (Y-AXIS) LOADINGS MATRIX	
Connection	**Loading Value**
M.Asking Questions & M.Making Design Choices	+.43
M.Asking Questions & **J.Customer/Consultant Requests**	+.43
M.Experimental Testing & **J.Performance Parameters/Requirements**	-.51
M.Experimental Testing & J.Communication	-.33

As mentioned in the methods section, the interpretation of the metric space becomes clearer when examining the values of the node positions (Table 5). The node positions are calculated from an optimization routine which minimizes the distance between the centroids and the projected points. The correlation reported for this analysis was r = 1, which means the locations of the centroids and projected points were identical. Examining the node positions clarifies the claim that the positive x-axis can be interpreted as connections to customer/performance rationale (M.Making Design Choices, J.Customer/Consultant Requests, and J.Performance Parameters), the negative x-axis as connections to communication rationale (J.Communication, M.Asking Questions), the positive y-axis as connections social moves (M.Asking Questions), and the negative y-axis as connections to technical/experimental moves (M.Experimental Testing) (Figure 11).

Table 5. Node positions calculated from the optimization routine for mean rotation dimension (x-axis) and svd dimension (y-axis).

CODE	**MEAN ROTATION (X-AXIS) NODE POSITION**	**SVD DIMENSION (Y-AXIS) NODE POSITION**
M.Making Design Choices	+3.5	+.83
J.Customer/Consultant Requests	+2.5	-.49
J.Performance Parameters	+3.0	-.54
M.Experimental Testing	-1.2	-2.6
M.Asking Questions	-2.4	+1.8
J.Communication	-3.0	-.69

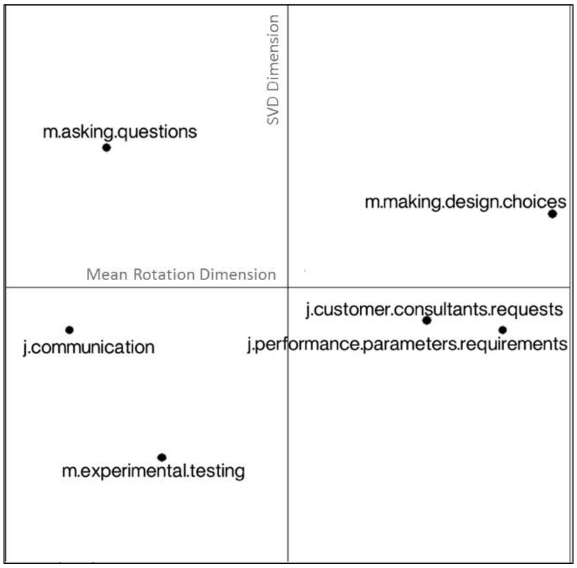


Figure 11. Plot of the node positions using the values from Table 5 for the mean rotation dimension (x-axis) and svd dimension (y-axis).

Thus, the space defined by the first dimension on the x-axis showed differences *between* the experts and novices: expert centroids were plotted further to the right because they incorporated more rationale based on customers and performance parameters whereas novice centroids were plotted further to the left because they focused on rationale based on communication. The second dimension on the y-axis showed differences *within* novices and experts in their design approaches and whether they focused more on the social or the technical moves of engineering design.

SUMMARY

In sum, the results show differences between expert engineers' and interns' densities and patterns of connections among moves and rationale in their discourse as initially revealed by the qualitative analysis and then echoed and extended by the network and centroid quantitative analysis. Experts had higher weighted densities among moves and rationale than novices, meaning that experts made more connections and stronger connections than novices. More important, the patterns of connections differed between experts and novices: experts made more connections with a variety of rationales such as performance parameters and customer requests, while novices mainly based their moves on the efficiency of communication. In addition, experts incorporated more than one move and more than one form of rationale at a time as indicated by their connections between rationale and between moves. Thus, experts had more sophisticated patterns of connections among moves and rationale than novices.

CHAPTER 4

PART TWO: VIRTUAL INTERNSHIP

METHODS

OVERVIEW

In Part Two, I applied the same grounded coding scheme developed from the real-world internship to virtual internship data which consisted of students' chat discourse from a design activity in which students selected five prototypes as a team to submit for testing purposes. I conducted a qualitative analysis focusing on two students—one high-outcome and one low-outcome—to identify differences in patterns of connections among moves and rationale. Then, I used ENA to conduct a quantitative network analysis.

VIRTUAL INTERNSHIP

Nephrotex is an 8-week long engineering virtual internship program in which students role-play as interns at a fictional biomedical engineering design company, where they work on teams to design dialyzers for hemodialysis machines (Chesler et al., 2012). Research and design activities and team interactions all take place through the web platform that supports the internship. Students begin by logging into the company website, which includes an email and chat interface. Acting as interns, they send and receive emails to and from their supervisor (a non-player character) and use the chat window for instant messaging with other team members and their assigned design advisor.

After conducting background research within the *Nephrotex* website, interns examine company research reports based on actual experimental data with a variety of polymeric materials, chemical surfactants, carbon nanotubes, and manufacturing processes. After collecting and summarizing research data, interns begin the actual design process using the simulated engineering drawing tool. First individually and then in teams, students develop hypotheses based on their research, test these hypotheses in the provided design space, and analyze the results provided. Interns also become knowledgeable about internal stakeholders within the company who have a stake in the outcome of their designed prototype. These stakeholders value different outputs, which are essentially performance criteria. Each of the five internal stakeholders in *Nephrotex* prioritizes two output parameters and identifies specific threshold values for each output. For example, the clinical engineer would like a high degree of biocompatibility and high flux, and the manufacturing engineer would like a device with high reliability but low cost. The stakeholders' concerns are often in conflict with one another (e.g., as flux increases, cost also increases), reflecting the conflicting demands common in professional engineering design. During the second half of the internship, students switch teams and inform their new team members of the research they have conducted thus far in the internship. In the new teams, students test more devices, analyze the second iteration of results, and make a choice for a final prototype. During the final days of the internship, students present their final device design and justify their design decisions to the class and instructor, then complete an exit interview with survey questions about their attitudes towards the engineering profession.

PARTICIPANTS AND DATA COLLECTION

Participants were first-year undergraduate engineering students. These students were enrolled in an introductory engineering course in which they participated in *Nephrotex*.

I collected data from students in *Nephrotex* in two forms (1) chat logs from teams of students from one activity in the program and (2) each student's engineering notebook entries from the end of that same activity. The chat logs were analyzed for connected design rationale and the notebooks provided evidence of their individual design performance, which was the basis for separating students into two groups—low and high outcome.

The data were collected from nine instances of *Nephrotex* which took place in 2015. All nine instances contained five teams of three to five students each, for a total of 45 teams and 197 students overall.

SEGMENTATION AND CODING

CHAT LOGS

Chat logs from the virtual internship were segmented by *utterance*—every time someone sends a response in a conversation. I then applied the same coding scheme that was developed from the real-world internship analysis.

Table 4. Connected design rationale coding scheme for virtual internship chats.

Code	**Description**	**Examples**
J.Customer/Consultant Requests	Justifying design choices/devices or strategies by stating that they meet or should meet customer/consultant requests.	*Hey, I was thinking if we should base it off of 5 of our consultants,* ***because if I want to test one nanotube for my consultant.***
J.Performance Parameters/Requirements	Justifying design choices/devices or strategies by referring to general performance parameters or specific results either from documentation/papers or results from their own testing. The reference to the documentation or	*I feel like we should really look into the manufacturing process of Phase Inversion* ***because it seems to keep flux high and it is in the middle when it comes to cost.***

	performance results does NOT to be explicit.	
J.Communication	Justifying design choices/devices or strategies by referring to facilitating communication efforts among colleagues or among engineers and customers.	*Lets all put our stuff in the shared space* ***so we all can see***
M.Experimental Testing	Setting up an experiment by using a control device or have constants and changing one variable at a time. Or using experimental tools or techniques to understand technical features of a product.	***I thought we were changing one variable at a time.*** *1 is the control. 2 is a different nanotube percent. 3 and 4 are different surfactants, and 5 is a different process*
M.Making Design Choices	Choosing a specification or characteristic for a prototype or design product.	***We should go with hydrophilic for the third prototype.***
M.Asking Questions	Asking questions or referring to the move of asking questions	***do you guys think cost matters?***

Because I obtained a high volume of data from students' chat logs (19,424 utterances), I used the tool, nCoder, to develop an automated coding algorithm to code the chats (Eagan et al., 2017; Shaffer et al., 2015). The nCoder allows researchers to develop and validate automated coding schemes. Additionally, the nCoder provides a statistic, rho, that functions like a p-value. If rho is less than .05, then the results from the sample which was coded can be generalized to a larger dataset.

Two raters were trained and then inter-rater reliability was calculated. To automate the coding scheme, I developed procedural definitions based on the conceptual definition of each code.

A procedural definition is any set of explicit rules that attempt to describe the data to which the code should and should not be applied. More precisely, I identified key words and regular expressions to enable automated detection for each code. For example, one regular expression for the procedural definition for coding for justifications includes searching for the word “thus,” but not for the phrase “thus far.”

A conceptual definition of a code is validated by having two (or multiple) raters code the data. A procedural definition is validated by having a computer apply the coding algorithm specified in the procedural definition and comparing the results to those of a human rater who used the conceptual definition to code. Thus, I measured the reliability between one human rater and the computer where the human rater used the conceptual definition and the computer used the procedural definition. When the human and the computer disagreed, I refined the procedural definition until I reached acceptable agreement and rho values. Once human and the computer reached acceptable agreement values, I concluded that the procedural definition reliably implements the conceptual definition.

The inter-rater reliability results for the virtual internships chat logs show that all pairwise agreements among rater one, rater two, and the computer had rho values of less than .05, which means the kappa statistic from the coded sample can be generalized to the entire dataset (Table 6). Cohen’s kappa values ranged from .71 – 1.0.

Table 6. Cohen’s Kappa among Rater 1, Rater 2, and the Computer for Virtual Internships Chat Codes.

Code	**Rater 1 & Computer**	**Rater 2 & Computer**	**Rater 1 & Rater 2**
J.Customer/Consultant Requests	.91**	.91**	1.0**

J.Performance Parameters/Requirements	.80**	.75*	.71*
J.Communication	.82**	.79**	.80**
M.Experimental Testing	.86*	.73*	.85**
M.Making Design Choices	.84**	.73*	.88**
M.Asking Questions	.89**	.87**	.98**

* Rho < .05   ** Rho < .01

Epistemic Network Analysis

For Part Two, I used ENA to create discourse networks for the virtual internship students. The ENA method used was identical to the method described in Part One, but the co-occurrences were identified differently. Because the virtual internship discourse data was in the form of chat conversations, I used a *moving stanza window* model (Siebert-Evenstone et al., 2016). In this approach, co-occurrences are identified not only within one person's utterance but also among people in the conversation within a window of utterances. This window slides along the chat data and accumulates co-occurrences of codes for each person within their own utterance and to their teammates' utterances that occurred before their own with the given window segment.

In addition to identifying co-occurrences within conversations with a moving stanza window, I used another feature of ENA to effectively compare the results from the real-world and virtual internship. As mentioned in the methods section in Part One, to visualize the sphere-normalized adjacency vectors, ENA performs a dimensional reduction on the high-dimensional space using either a mean-rotated method or a singular value decomposition. This provides a rotation of the original high-dimensional ENA space, but captures the maximum variance in the data. The space can be interpreted by examining the loadings, or basis vectors, from the data rotation method.

One benefit to using such data-reduction methods is the ability to “freeze” the space by using the same loadings for another set of data. In the analysis of the virtual internship students, I used the loadings matrix created from the real-world internship. More specifically, I applied the same coding scheme and same number of co-occurrences, created a normalized, cumulative adjacency vector for each virtual internship student, and multiplied these students’ adjacency vectors by the loadings matrix created from the real-world internship analysis from Part One.

NOTEBOOKS ENTRIES

In addition to examining the chat data, I analyzed student engineering notebooks which students completed at the end of the activity. The notebooks served as evidence of individual design performance in the virtual internship. During the program, student notebooks contained pre-determined sections such as “List of five prototypes” or “Justifications for the selection of five prototypes.” I used these pre-determined sections to segment the notebook data and code each section.

After the notebooks were segmented, I used a variation of the Delphi method to develop a coding scheme for the quality of student notebooks. In general, the Delphi method is an iterative process to collect the judgments and feedback of a panel of experts and apply this feedback to a qualitative analysis and interpretation of data (Dalkey, Brown, & Cochran, 1969; Rowe & Wright, 1999). For this study, two domain experts—an engineering educator and a professional engineer—examined the notebooks and developed a rubric that identifies high quality design work (Table 7).

Table 7. Rubric for Evaluating Quality of Individual Notebook Entries. Maximum Score = 10, Minimum Score = 0.

Criteria	**Category**	**Good (2 points)**	**Fair (1 point)**	**Poor / NA (0 points)**

A	**Team skills**	Acknowledgement of team member contributions. Mention team member(s) by name and provide record of accomplishments.	Team is mentioned but team member contributions not noted.	No mention is made of team.
B	**Technical Resources**	Uses (cites) 2 or more technical reports	Cites 1 technical report	No report citations
C	**Stakeholder Citations**	Uses (cites) all five stakeholder requirements or preferences.	Cites at least 1 stakeholder.	No stakeholders cited
D	**Design Justification**	Makes justifications based on both quantitative and qualitative analysis	Makes justification based on EITHER quantitative OR qualitative analysis	Unjustified design decision
E	**Testing Plan Logic**	An approach to new design testing is coherent – using a control device for comparison or testing extremes. Has a full testing plan that is clear for all five devices.	Approach to design testing is partial. Plan is not applied to all five devices.	No clear approach

After the rubric was developed, the two experts and I coded a sample of 48 notebook entries using this rubric. Then, I developed an automated coding algorithm to code the remainder of the notebooks. To assess the validity of the rubric, I measured the inter-rater reliability using Intraclass correlation (ICC) (Shrout & Fleiss, 1979). This method is appropriate in this situation because ICC (1) measures agreement among ratings that are non-binary, (2) measures agreement among multiple raters, and (3) provides confidence intervals around the test statistic.

The inter-rater reliability results for the notebook entries show that the average ICC metric for a two-way multi-rater agreement was .75 with a 95% confidence interval from .64 to .83 (F (47,142) = 13, p < .001).

The median score of the notebooks was calculated and used to classify students as high and low outcome. If a student received a notebook score higher than the median score of 4, then they were identified as high outcome and if a student received a notebook score lower than the median score of 4, then they were identified as low outcome, which resulted in 64 low outcome students and 133 high outcome students.

RESULTS

Nephrotex is a virtual engineering internships where first-year undergraduate students play the role of interns at a biomedical device company. Students are tasked with designing a filtration membrane for a hemodialysis machine and complete a variety of activities including individually conducting research on filtration principles, communicating with their teammates to share information about their research, and selecting prototypes to submit for testing. All activities take place online in a simulated company platform in which students chat with their team members, send emails to their boss, and use simulated engineering drawing tools to design prototypes.

In what follows, I examined discourse from one design activity in *Nephrotex* in which students met with their team members in the chat tool to discuss their research thus far and decided collectively on five prototypes to send to the lab for testing. The results presented here in Part Two focus on the chat discourse of one representative low-outcome student, Grace, and one representative high-outcome student, Levi, to provide an in-depth examination of connections among moves and rationale in the virtual internship.

LOW-OUTCOME STUDENT

After individually reading *Nephrotex* research reports on the various design parameters, students held a meeting in the online chat tool with their team members to discuss what they've learned so far and to decide on a batch of five devices to submit to the lab for testing.

This section focuses on Grace, a low-outcome student, who was in a group with four other individuals: David, Jared, Matthew, and Austin.

At the start of discussion Jared asked, "OK so which prototypes should we use for our batches?"

Austin advocated for one of Grace's prototypes which used a hydrophilic surfactant, which he claimed was the most reliable and the cheapest surfactant choice. David continued the conversation:

> David: I'm hearing hydrophilic so that sounds like our best bet.
>
> Austin: but the biological one has a low percentage of blood cell reactivity which is good
>
> **Grace: Are you talking about making new prototypes [or] are you still looking at the already made ones?**
>
> Jared: I think we should stick with the ones that are already made since that would make it easier.

David and Austin offered suggestions for which surfactant to choose. However, Grace did not offer suggestions for a surfactant, but instead asked a clarifying question about whether the team was making new prototypes.

In this excerpt, Grace connected the move of asking questions: "Are you talking about making new prototypes [or] are you still looking at the already made ones?" to David's move of making a design decision: "I'm hearing hydrophilic so sounds like our best bet" and to Austin's justification based on performance parameters: “the biological one has a low percentage of blood cell reactivity which is good.”

Later in the discussion, the team decided to use Grace’s previously designed prototype as one of the devices to submit for testing. Austin asked Grace to explain her reasoning for choosing 4% carbon nanotube for her device:

> Austin: Reason for going with 4% nanotube?
>
> **Grace: Just because it was the highest percentage that I could see data for and therefore the highest I could trust 100%**

In this moment, Grace connected the rationale of performance parameter: “it was the highest percentage that I could see data for” to Austin’s move of asking questions: “Reason for going with 4% nanotube?”

In contrast to the previous exchange, Grace answered a question instead of asking a question but still made connections to the move of asking questions.

Continuing the conversation, David pushed back on Grace’s justification about the performance of using 4% carbon nanotubes as opposed to 1%; he believed 1% was more cost effective and still had desirable performance. Grace did not respond, so Austin made a proposal:

> Austin: Alright how about this. We go with the biological surfactant with a low cnt % since the blood cell reactivity is already low
>
> Austin: this keeps the device at a decent price while making it more marketable
>
> **Grace: So, are you talking about making a new prototype then?**
>
> Austin: Not necessarily, just decrease the CNT%
>
> David: I think that reasoning is sound.

After Austin proposed and justified using a biological surfactant with a low carbon nanotube percentage, Grace asked a follow-up question.

Once again, Grace connected the move of asking questions: “So are you talking about making a new prototype then?” with Austin’s move of a design decision and justification of performance parameters: “We go with the biological surfactant with a low cnt%...this keeps the device at a decent price while making it more marketable.”

In sum, Grace’s talk centered on asking clarifying questions and providing direct responses to questions asked by her team members. Visualizing her talk as a discourse network, confirms this finding (Figure 12). The connections in her discourse network focused on the move of asking questions, which she connected to making design decisions and justifications about communication and performance parameters. The strongest connections in her network are between the move of asking questions and making design choices and between the move of asking questions and the justification of performance parameters.

Figure 12. Example of a low-outcome student (Grace) discourse network.

HIGH-OUTCOME STUDENT

In contrast to Grace's discourse network which had a central focus of asking and answering questions, Levi, a high-outcome student, made connections among a variety of moves and rationale.

Levi was on a team with three other individuals: Francesca, Priya, and Lee. When it was time to start the meeting, Levi initiated the discussion by typing, "Okay everybody, so we are looking at the prototypes in the FEEDS option under the tools tab."

Levi continued the discussion:

> **Levi: So we don't have to type out all of the explanations for each prototype again, would you just like to put that notebook in the shared space file and then read each others explanations and go from there? I think we might want to choose some of each based on explanations.**
>
> Francesca: how do you do that?
>
> **Levi: Go to the "individuals design 5 prototypes Notebook" under the notebook tab, on the top left of the notebook you should see a box that says "available in shared space" next to it. Just click that box.**
>
> Francesca: okay i did
>
> **Levi: Awesome! Okay so we'll read each other's justifications and then discuss prototypes.**
>
> Francesca: okay sounds good!

In this excerpt, Levi connected the moves of making design decision: "I think we might want to choose…" and asking questions: "Would you just like to… read each others explanations and go from there?" to the rationale of communicating with his teammates: "So that we don't have to type out all the explanations for each prototype again."

After gaining access to their team members' notes, Francesca asked if the team should only choose two different surfactants, biological and steric hindrance:

> Francesca: Do you think we should pick either steric or biological for all of them? or choose some of each?
>
> Francesca: I feel like if we have a lot of different variants we wont have anything to really compare our results with
>
> **Levi: I like the idea of using mainly steric hindrance because it was the most versatile surfactant and voted the best choice by our group previously, but i think we should try to include at least one prototype using a different surfactant to test the results of changing a surfactant.**
>
> Francesca: okay that sounds good...do you want to do 3 and 2?
>
> Francesca: Want to do the three steric having 1.5% nanotube and then do one vapor, one dry-jet wet, and one phase?
>
> **Levi: Sure, that sounds good if we can find enough similarities between at least two designs to justify comparing the results of each to each other. Like each design has a different design that varies by only one factor so we can compare results.**

In this excerpt, Levi connected the moves of making design decisions: "I like the idea of using mainly steric hindrance…" to the rationale of performance: "because it was the most versatile surfactant and voted the best by our group previously." These specific connections were made within his own utterance. However, these statements also connected to Francesca's previous utterances in which she asked a question about choosing design specifications: "Do you think we should pick either steric or biological for all of them?" and proposed an experimental approach: "I feel like if we have a lot of different variants we wont have anything to really compare our results with."

A few lines later, Levi clarified the experimental approach that Francesca suggested, further strengthening his connections among the moves of experimental testing, asking questions, and making design decisions.

In sum, Levi made a variety of connections among moves and rationale, mostly focusing on the move of making design decisions. Visualizing his talk as a discourse network, confirms this finding (Figure 13). His strongest connections were among making design decisions, asking questions, and suggesting an experimental approach for testing. However, Levi also connected asking questions to justifications centered on better team communication as well as making design decisions based on the high performance parameters of a design choice.

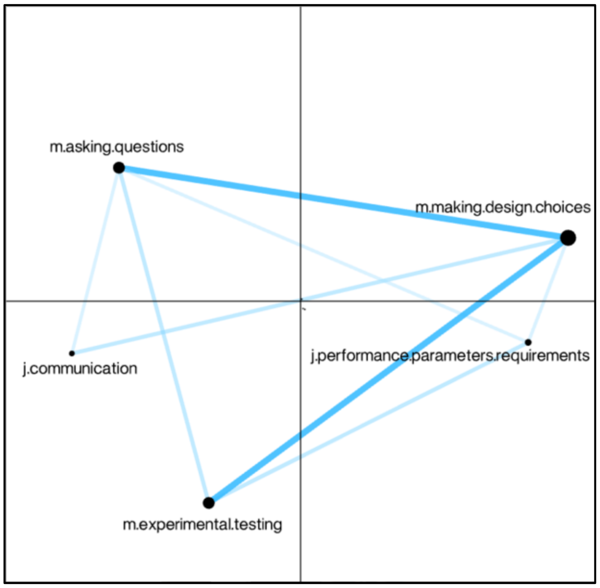


Figure 13. Example of a high-outcome student (Levi) discourse network.

SUMMARY

In sum, the results show differences between one low-outcome students' and one high-outcome students' patterns of connections among moves and rationale in their discourse as initially revealed by the qualitative analysis and then confirmed by the network analysis. Levi, the high-outcome students made more connections with a variety of moves and rationales, while Grace, the low-outcome student, focused mainly on the move of asking questions. Grace either asked clarifying questions in response to her teammates' moves and rationale or she directly answered questions from her teammates. Levi connected to the move of asking questions as well, but also had strong connections among the move of experimental testing, the move of making design decisions, and the justification of performance parameters suggesting a more sophisticated pattern of connections than Grace.

CHAPTER 5

PART THREE: COMPARING THE REAL-WORLD AND VIRTUAL INTERNSHIP

METHODS

OVERVIEW

Because both Part Three and Part Two examined student data from the virtual internship, *Nephrotex*, the same methods from Part Two were used for the analysis in Part Three. I used the same two datasets: chat logs from teams of students from one activity in the program and each student's engineering notebook entries from the end of that same activity. The data were collected from nine instances of *Nephrotex* which took place in 2015. All nine instances contained five teams of three to five students each, for a total of 45 teams and 197 students overall.

The chat logs were analyzed for connected design rationale and the notebooks provided evidence of their individual design performance, which was the basis for separating students into two groups—low and high outcome. As described in Part Two, I coded the chat logs using nCoder (Eagan et al., 2017; Shaffer et al., 2015), an automated coding tool, and two engineers and I use the Delphi method (Dalkey et al., 1969; Rowe & Wright, 1999) to create a rubric and grade the notebooks, which was then also automated. Students who scored higher than the median notebook grade were identified as high-outcome and students who scored lower than the median notebook grade were identified as low-outcome. The chats logs were analyzed for connected design rationale using ENA.

EPISTEMIC NETWORK ANALYSIS

As described in Part Two, because the virtual internship discourse data was in the form of chat conversations, I used a moving stanza window model in which co-occurrences are identified not only within one person's utterance but also among people in the conversation within a window of utterances (Siebert-Evenstone et al., 2016). In addition, I used the loadings matrix created from the real-world internship and thus, Part Two and Part Three employ the same coding scheme and same number of co-occurrences as the real-world internship analysis in Part One.

Because Part Three scales up the results from Part Two, I used an additional feature of ENA to effectively compare a large number of networks at one time: the centroid representation. Once the virtual internship student data were projected into the real-world internship space, I calculated the mean centroid for the low-outcome students and the mean centroid for the high-outcome students. Then, I conducted a Student's t-test to determine if there were significant differences between low and high outcome student discourse networks in the real-world internship space.

RESULTS

Part Three scales up the results from Part Two by quantitatively examining 197 *Nephrotex* students' discourse networks. The following analysis for Part Three interprets the virtual internship student data in the context of an authentic internship by using ENA to plot the virtual internship students' discourse networks and centroids into the real-world internship metric space created from the limited set of networks in Part One. Specifically, I investigate whether high-outcome students have patterns of connections more like those of experts than low-outcome students.

NETWORK ANALYSIS

First, I examined the network representations for the low and high outcome students. If a student received a notebook score higher than the median score of 4, then they were identified as high outcome, and if a student received a notebook score lower than the median score of 4, then they were identified as low outcome. This resulted in 64 low outcome students and 133 high outcome students. To compare the two groups, I created a mean network of the low and high outcome students (Figure 14). This representation averages the weights of the links for each group of interest.

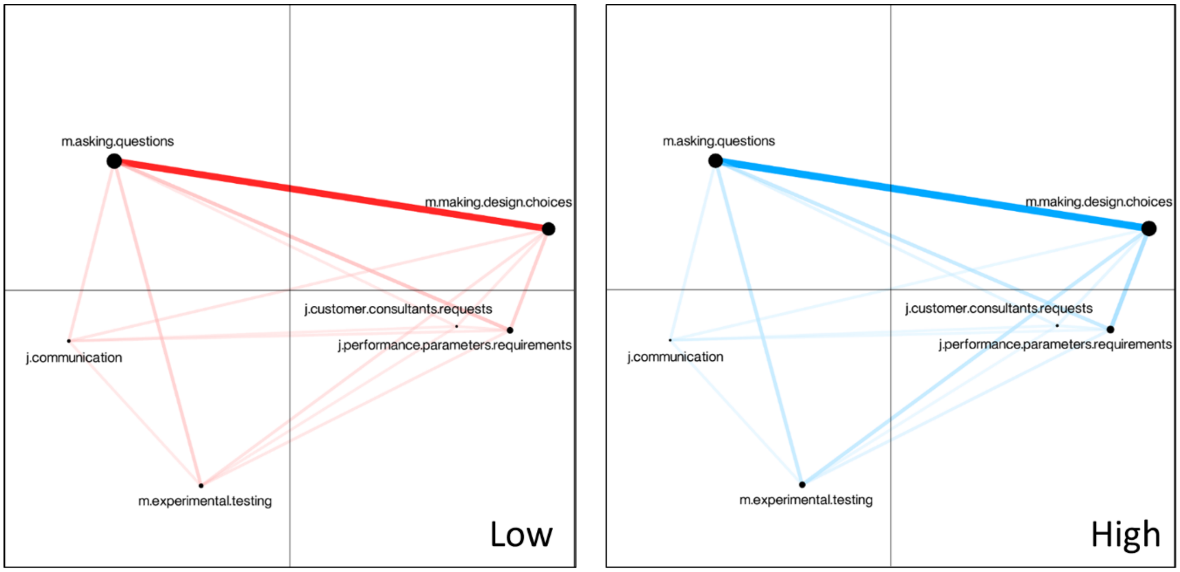


Figure 14. Mean network representations of low-outcome (left) and high-outcome students (right). This is average of the network weights for each group.

To more clearly compare the low and high outcome student networks, I created a subtracted network, which enables identification of the most salient differences between the two networks of interest. Figure 15 shows a subtracted network between the mean networks of the high-outcome and low-outcome students in which the weights of the two mean networks have been subtracted to obtain one network representation. The difference in weights for six selected connections are reported in the figure. These six connections were selected because they were the largest reported differences between experts and novices in the real-world analysis from Part One.

The subtracted network suggests that high-outcome students had different patterns of connections than low-outcome students. When examining the patterns of connections, low-outcome students had stronger connections to the justification of communication than high-outcome students. In contrast, high-outcome students generally had stronger connections with all remaining moves and rationale with the strongest connection being between making design choices and justifications based on performance parameters.

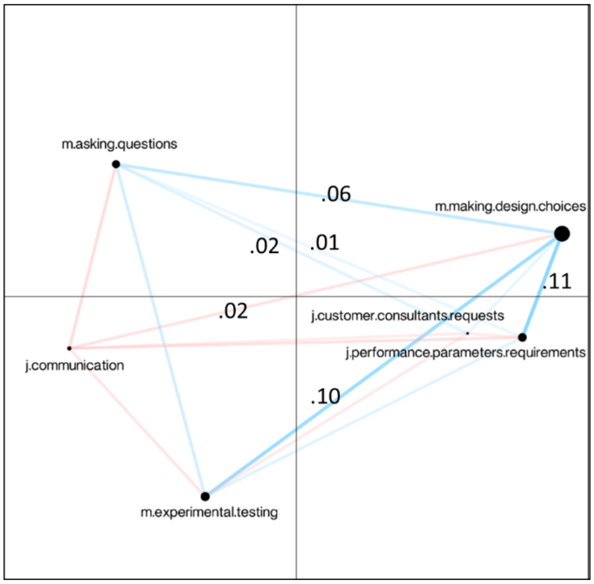


Figure 15. A subtracted network comparison between high-outcome (blue) and low-outcome (red) student discourse networks. This representation is the result of the difference in weights between the mean high-outcome student network and the mean low-outcome student network. The largest six differences in terms of weights were determined from the real-world internship analysis and are now shown for the virtual internship analysis.

Notably, the differences between high and low outcome students were reminiscent of the differences observed between the two expert engineers and the two senior interns found in Part One. Comparing the subtracted networks from the real-world internship in Part One and the virtual internship (Figure 16) suggests that the novice interns and the low-outcome students had similar patterns of connections: networks with stronger connections to the justification of communication. In turn, the expert engineers and the high-outcome students had similar patterns of connections: networks with stronger connections to the move of making design choices and rationale based on the customer requests and the performance parameters. Not surprisingly, because the experts had far more experience with design work than the interns or the students, they had more strongly weighted connections than the high-outcome students, and thus the difference between experts and novices in the real-world internship is more prominent than the difference between high and low outcome students in the virtual internship. However, the results suggest that high-outcome students may be beginning to develop similar patterns of connections than those of experts, whereas interns and low-outcome students may be still lacking many of the connections that are representative of expert-like thinking.

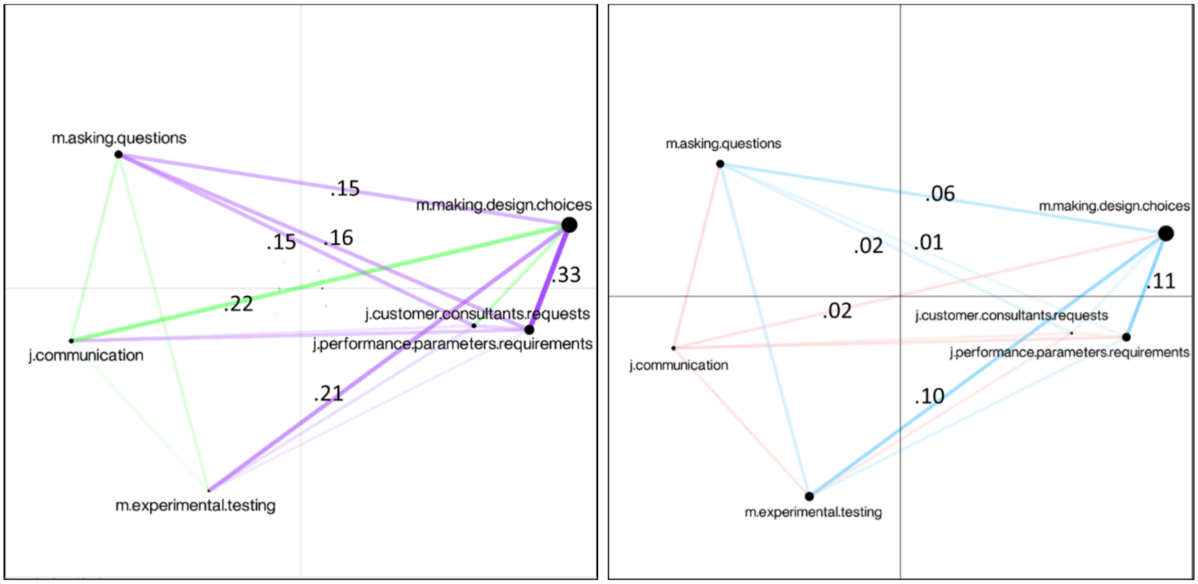
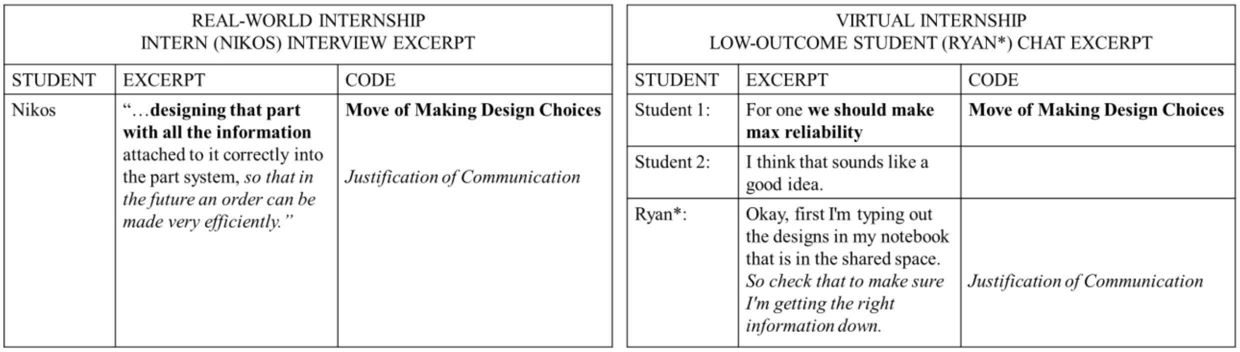


Figure 16. Side-by-side comparison of the subtracted networks from the real-world internship between novice interns (green) and expert engineers (purple) and the virtual internship between low (red) and high (blue) outcome students. The largest six differences in terms of weights were determined from the real-world internship analysis and are shown for the virtual internship analysis.

In addition to the network representations, the similarities between the novices/low-outcome students and the experts/high-outcome students can be seen qualitatively. For example, figure 17 shows a comparison of one intern's interview response and one low-outcome student's chat excerpt. The intern from the real-world internship, Nikos, connected the move of making design choices ("designing that part with all the information") to the rationale of effective communication ("so that in the future an order can be made very efficiently"). Similarly, the example excerpt from the low-outcome student, Ryan, shows parallel patterns of connections. In his team chat, a student made a move of making a design choice ("we should make max reliability") and Ryan responded and connected to this utterance with a justification based on communication ("so check that to make sure I'm getting the right information down"). Both examples from the intern and the low-outcome student show connections being made between the move of making design choices and the justification of communication, which were the prominent connections made in their respective discourse networks.



REAL-WORLD INTERNSHIP
INTERN (NIKOS) INTERVIEW EXCERPT

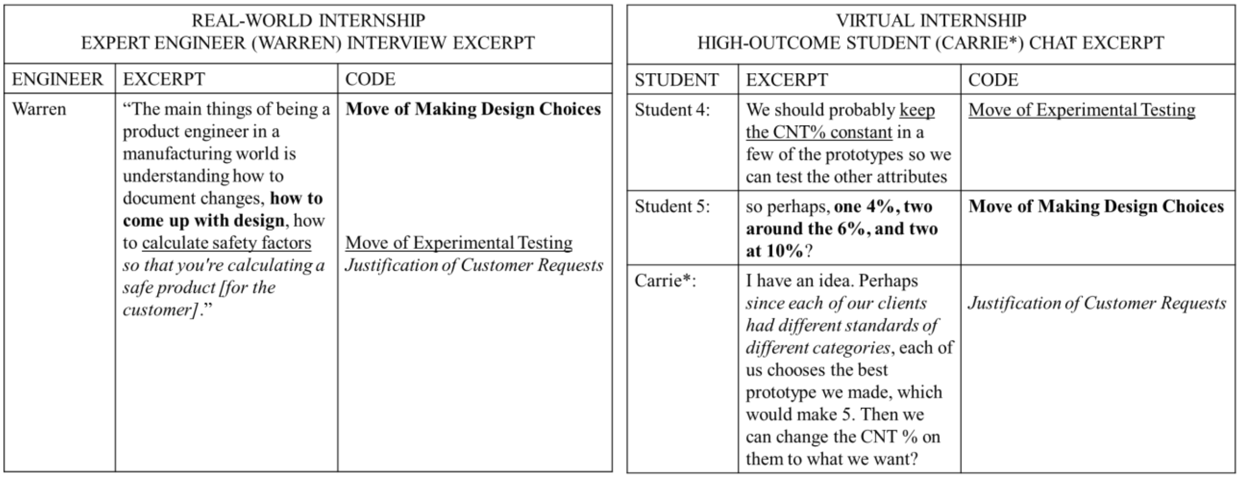
STUDENT	EXCERPT	CODE
Nikos	"…**designing that part with all the information** attached to it correctly into the part system, *so that in the future an order can be made very efficiently."*	**Move of Making Design Choices** *Justification of Communication*

VIRTUAL INTERNSHIP
LOW-OUTCOME STUDENT (RYAN*) CHAT EXCERPT

STUDENT	EXCERPT	CODE
Student 1:	For one **we should make max reliability**	**Move of Making Design Choices**
Student 2:	I think that sounds like a good idea.	
Ryan*:	Okay, first I'm typing out the designs in my notebook that is in the shared space. *So check that to make sure I'm getting the right information down.*	*Justification of Communication*

Figure 17. Side-by-side comparison of examples of intern (left) and low-outcome student (right) discourse.

Accordingly, figure 18 shows a comparison of one engineer's interview response and one high-outcome student's chat excerpt. The engineer from the real-world internship, Warren, connected the move of making design choices ("…how to come up with design…") to the move of experimental/technical testing ("…calculate safety factors") and to the rationale of customer requests ("so that you're calculating a safe product [for the customer]"). Similarly, the example excerpt from the high-outcome student, Carrie, shows parallel patterns of connections. In Carrie's team chat, a teammate made a move of experimental testing ("We should probably keep the CNT% constant"). Another student responded with a move of making design choices ("one 4%, two around the 6%, and two at 10%?"). In response, Carrie connected to both of these utterances with a justification based on customer requests ("I have an idea. Perhaps since each of our clients had different standards of different categories…"). Both examples from the expert engineer and the high-outcome student show connections being made among the move of making design choices, the move of experimental testing, and rationale based on customer requests, which were the prominent connections made in their respective discourse networks.



REAL-WORLD INTERNSHIP EXPERT ENGINEER (WARREN) INTERVIEW EXCERPT		
ENGINEER	EXCERPT	CODE
Warren	"The main things of being a product engineer in a manufacturing world is understanding how to document changes, **how to come up with design**, how to calculate safety factors *so that you're calculating a safe product [for the customer]*."	**Move of Making Design Choices** Move of Experimental Testing *Justification of Customer Requests*

VIRTUAL INTERNSHIP HIGH-OUTCOME STUDENT (CARRIE*) CHAT EXCERPT		
STUDENT	EXCERPT	CODE
Student 4:	We should probably keep the CNT% constant in a few of the prototypes so we can test the other attributes	Move of Experimental Testing
Student 5:	so perhaps, **one 4%, two around the 6%, and two at 10%**?	**Move of Making Design Choices**
Carrie*:	I have an idea. Perhaps *since each of our clients had different standards of different categories*, each of us chooses the best prototype we made, which would make 5. Then we can change the CNT % on them to what we want?	*Justification of Customer Requests*

Figure 18. Side-by-side comparison of examples of expert engineer (left) and high-outcome student (right) discourse.

Thus, the quantitative networks and qualitative examples suggest that across two different design learning practica, a real-world company internship and a virtual internship, we can see analogous differences between relative novices and relative experts in terms of their connections among moves and rationale.

CENTROID ANALYSIS

The analysis of the centroids of the networks projected into the real-world internship space confirms and extends these results (Figure 19). As shown from the analysis in Part One, in this space, a high score on the x-axis represented more expert-like connections, focusing on customer and performance parameters rationale and a low score represented more novice-like connections, focusing on communication rationale. A high score on the y-axis represents a focus on social aspects such as asking questions and a customer-focus, while a low score on the y-axis represents a focus on technical aspects of design work such as using experimental methods.

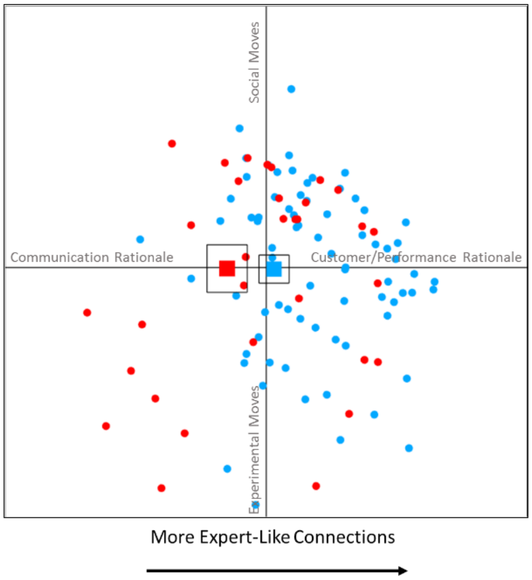


Figure 19. Virtual internship students plotted in expert metric space. Plot shows significant differences between low (red) and high (blue) outcome virtual internship students on the x-axis. Higher on the x-axis indicates more connections with customer/performance rationale which are more expert-like connections.

High-outcome students' (M = .34, SD = .23) had significantly higher discourse network centroids in the *x-direction* than low-outcome students' (M = .36, SD = .21; t (109.3) = 3.7, p < .001) with a high effect size (d = .55). This shows the high-outcome students' mean value was higher on the axis that determines expertise than the low-outcome students'. Thus, high-outcome students had patterns of connections that were more like experts and focused on connections to customer and performance parameters rationale when making design decisions. This finding aligns with the network and the qualitative analysis above.

There was no significant difference between high (M = .14, SD = .21) and low (M = .15, SD = .25) outcome students in the *y-direction* (t (109.3) = .04, p = .97) indicating that there were no differences among low and high outcome students in terms of social vs. technical move making.

Finally, high-outcome students' (M = .09, SD = .05) had significantly higher discourse *weighted network densities* than low-outcome students' (M = .07, SD = .05; t (109.3) = 2.3, p = .02) with a moderate effect size (d = .35). This finding aligns with the network analysis above which showed that high-outcome students made more connections among moves and rationale than low-outcome students. Table 8 summarizes the three Student's t-tests conducted on student centroid values from the first dimension, second dimension, and weighted densities.

Table 8. Summary of three t-tests conducted on the centroid values from first dimension, centroid values from second dimension, and on weighted densities using virtual internship networks. The tests determine whether there is a statistically significant difference between high and low outcome students on each dimension and for weighted densities.

Results	**Mean**	**Standard Deviation**	**Test Statistic (Student's t) & Effect Size (Cohen's D)**
First Dimension Customer/Performance Rationale & Expert-like Connections (positive x-axis) vs. Communication Rationale & Novice-like Connections (negative x-axis)	High outcome: .34 Low outcome: .36	High outcome: .23 Low outcome: .21	t (109.3) = 3.7* d = .55
Second Dimension Social Moves (positive y-axis) vs. Technical Moves (negative y-axis)	High outcome: .14 Low outcome: .15	High outcome: .21 Low outcome: .25	t (109.3) = .04 d = .01

Weighted Network Densities Measurement of how many connections were made and the weights of connections	High outcome: .09 Low outcome: .07	High outcome: .05 Low outcome: .05	t (109.3) = 2.3* d = .35

* p < .05

SUMMARY

In sum, there were significant differences between low and high outcome virtual internship students as shown by network and centroid analysis. High outcome students had higher weighted densities among moves and rationale than low outcome students, meaning that high outcome students made more connections and stronger connections than low outcome students. More important, the patterns of connections differed between low and high outcome students: high-outcome students made more connections with a variety of rationales such as performance parameters and customer requests, while low-outcome students mainly based their moves on the efficiency of communication. Finally, as shown by a network comparison and qualitative examples, the differences in connections patterns among low and high outcome virtual internship students were similar to the differences in connection patterns between interns and expert engineers in the real-world internship. This finding is noteworthy because it shows the same patterns of differences and measurements between relative experts and relative novices across two different reflective design practica.

CHAPTER 6

DISCUSSION

SUMMARY OF FINDINGS

Design is a central activity in engineering and thus, is central to engineering education. Effective design learning occurs in real-world and virtual reflective practica in which novices interact with experts to learn the ways of the practice. Such learning spaces have the potential to help students develop complex design thinking. However, a significant issue in design education is how to assess and measure design learning as it emerges in authentic practices. Thus, the goal of this study is to provide one approach for modeling and measuring complex design learning.

The results in this study were segmented into three parts, all of which examined and measured connections among moves and rationale in discourse. Part One showed that participants from a real-world internship program made connections among moves and rationale and that expert engineers had different patterns of connections than student interns. Experts in the real-world internship made a variety of connections among moves and rationale, the most salient being specific to the domain of design such as making design decisions in order to meet performance requirements and making design decisions based on the customer's preferences. In contrast, senior interns focused mainly on making design decisions in order to improve the quality of communication during the design process. And finally, novice interns did not make any connections among moves and rationale.

Part Two showed that participants from a virtual internship program made connections among moves and rationale, and this analysis focused on two students—one high-outcome and one low-outcome—who had different patterns of connections. The high-outcome student had a denser network with a variety of connections among moves and rationale, whereas the low-outcome student had a sparser network that focused mainly on asking questions.

Part Three scaled up the results of the virtual internship by examining 197 virtual internship students and comparing their networks to those of the experts from the real-world internship. After projecting the virtual internship students' discourse networks into the real-world expert space, the results showed that high-outcome students had discourse networks that were more like experts than the low-outcome students. Finally, this analysis also showed that the same differences in patterns of connections that were revealed between relative novices and experts in the real-world internship were also revealed between relative novices and experts in the virtual internship.

Connected Design Rationale: Design Thinking Through A Learning Sciences Lens

Using ENA to measure connected design rationale, this study differentiated between engineering professionals and interns in a real-world internship program, between high and low outcome students in a virtual internship, and perhaps most importantly, between virtual internship students and professional engineers.

Authentic Design Learning Through Reflective Practica

I chose the GammaCorp and *Nephrotex* settings for this study because they are reflective design practica—spaces where learners experience a simulation of design work (Schön, 1987). In such spaces, learners interact with mentors through purposeful participant structures and pedagogy that facilitate reflection-on-action (Shaffer, 2005a). The results from the real-world ethnographic analysis revealed that such participant structures were present at GammaCorp. Interns engaged in both individual and group participant structures that were organized within the pedagogical method of the Informal Feedback Cycle (IFC). It was through the IFC that interns engaged in reflection-on-action with mentors and began to learn ways of thinking that are valued within the practice. Opportunities for reflection-on-action were also present in the virtual internship but were not described in detail because such arguments have been made in previous studies (see D'Angelo, Shaffer, & Chesler, 2011; Hatfield, 2015; Nash & Shaffer, 2008; Saucerman, Ruis, & Shaffer, 2017). Thus, the ethnographic methods in this study offer a more authentic approach towards investigating reflective design practice compared to studies which have been conducted in lab settings (Atman et al., 1999; Atman & Turns, 2001; Cross, Christiaans, & Dorst, 1994; Dorst & Cross, 2001). In addition, although real-world internships and co-op education are common among undergraduate engineering education programs, very little work has been done on how students learn design in workplace settings (Johri & Olds, 2011) and thus, this study provides preliminary insight into the learning and pedagogy which occur in engineering internships.

Not only do both the real-world and virtual settings have similar opportunities for reflection-on-action, the participants in both settings exhibited similar patterns of design cognition. This suggests that learners use similar design processes and approaches in both real-world and virtual environments. However, one of the main advantages of virtual learning is that digital data collection allows for the examination of large datasets (Hsu, 2014). Such records of student work offer a rich analysis of design learning in an authentic environment at a larger scale than with traditional, real-world ethnographic studies and as such, could provide more insight into how students learn design. Thus, the results in this study suggest that virtual reflective design practica, such as *Nephrotex*, are promising avenues for investigating and characterizing design thinking.

A Connected Model of Situated Action for Design Learning

The analysis of the engineer, intern, and student discourse in both the real-world and virtual setting showed that all participants made moves (Schön, 1987) and provided rationale (Rittel, 1987) in some form. However, examining the *connections* among moves and rationale in discourse differentiated among levels of expertise, not simply examining occurrences of moves and rationale as Schön and Rittel have suggested. The results showed that modeling connections among moves and rationale in Discourse revealed whether a sophisticated understanding of design practice exists. The experts and the high-outcome students who demonstrated this understanding could provide moves and rationale in a patterned and coherent web and were able to identify multiple moves or multiple rationale in one instance. These results support current learning sciences research which argue that characterizing complex thinking and learning requires investigating how learners understand relationships among domain-specific elements (diSessa, 1993; Linn et al., 2004; Shaffer, 2006).

More specifically, in this study understanding connections among concepts means *knowing-how*, making design moves, and *knowing-why*, the reasoning and rationale supporting such moves. Relying on the context of the design problem, a skilled designer chooses and enacts the appropriate combinations of knowing-how and knowing-why. This approach is essentially epistemological and situated. It is epistemological because it examines the justifications and reasoning processes for actions, and it is situated because the actions that designers take and the justifications they provide are dependent on each unique design scenario. However, *situated actions* are not just actions taken within a particular context, but more precisely, are the interactive relations between how learners perceive a situation in the world, how they make sense of the situation, and of course, how they interact with situation (Suchman, 1987, 2000). Clancey (1997) summarizes this relationship between the learner, the context, and actions as “new ways of seeing and ways of making changes to the world [that] develop together" (p. 344). Shaffer has extended this work and argues that not only should theories of learning include examining an individual's situated actions, but also the transformation of the individual as he or she becomes enculturated into a practice. As such, the work in this dissertation most closely aligns with epistemic frame theory (Shaffer, 2006, 2007a), which claims that learners exhibit ways of linking knowing and thinking when they become enculturated into a practice.

Both epistemic frames and connected design rationale are *models of situated action* which characterize enculturation by determining the extent to which a learner has adopted the Discourses of a community. Shaffer (2012) claims that such models do so by "explicitly connecting events at the sociocultural level (participation in a Discourse) with events at the individual level (actions of a player)" (p. 426). Other researchers have developed models of situated action in various domains (Greeno & Sande, 2007; Mislevy & Steinberg, 2003; Shute, Ventura, Zapata-rivera, & Bauer, 2009). For example, Arvaja and colleagues (2007) examined how pre-service teachers collaborate and develop lesson plans in web-based discussions and why some teachers were not as engaged as others. Barab and colleagues (2001) captured students' actions in the form of a network in a project-based astronomy course and claim that such networks could provide instructors insight into students' trajectories of learning and their interactions with other students and tools. And in this study, I constructed a model of design learning as it emerges in real-world and virtual practica and claim that this model can differentiate among expert and novice design thinking. This dissertation work is an example of a model of situated action which examines the culture of design thinking and provides a close examination of connections between knowing-how and knowing-why in Discourse within design practices. Thus, this study applied a learning sciences lens of situated action and connected learning to evaluate engineer and student discourse data to extend the research on design learning and thinking.

Using this lens, the results suggest that relative novices made fewer connections overall and focused mainly on rationale centered on effective communication. In contrast, relative experts had more connections overall and focused on domain-specific rationale such as customer requests and performance parameters. From a content learning perspective, these results align with Dym’s (1994) and others’ (Cross, 2007; Jonassen et al., 2006; Simon, 1996; Ulrich & Eppinger, 2011) descriptions of the design process which involve identifying the goals of a product and considering how the device meets performance and customer requirements.

From a learning model perspective, these results align with Atman and colleagues’ (2000; 1999; 2001) claims that experts prioritize identifying customer and performance constraints while novices focus on effective communication and planning. The results also partially align with Gero and colleagues’ (1998; 2008; 1998) model of design learning as a series of situated moves. Their model showed that experts have more organized knowledge structures than novices which lead to more efficient design practices. However, these learning models do not investigate rationales provided for actions nor explore the patterns of relationships among moves and rationale during reflection-on-action practices. This is problematic because both reflection-on-action (R. Adams, Turns, & Atman, 2003; Schön, 1987) and design rationale (Burge & Brown, 1999; Lee & Lai, 1991; Rittel, 1987; Shum & Hammond, 1994) are critical in authentic design practice. And as McCall and Burge (2016) have suggested, integrating theories of design rationale with reflection-on-action can provide more insight into the design process and help develop more general and useful theories of design. As such, one of the key contributions of this dissertation work is the integration of moves and rationale to provide a learning model of reflection-on-action in design thinking, and thus shed more light on the complex design process.

ENA AS A MEASUREMENT TOOL

In addition, this study contributes to other analyses which demonstrate the usability of ENA as a tool to measure connections in discourse and to assess complex design thinking (Arastoopour et al., 2014, 2016; Arastoopour & Shaffer, 2013; Hatfield, 2015; Knight, Arastoopour, Shaffer, Buckingham Shum, & Littleton, 2014; Nash & Shaffer, 2013; Svarovsky, 2011). As the results suggest, the key affordances of ENA are its ability to visualize the co-occurrences of qualitative codes through network representations, analyze a large sample size through centroid representations, and in turn, perform statistical tests to draw quantitative conclusions about connections made in qualitative data. Using these features in this study, ENA reproduced and highlighted important patterns of connections among moves and rationale in discourse and modeled this characterization of complex design learning in two different environments.

This study also established ENA as a tool for measuring the validity of a connected design rationale by correlating the network results with an outside outcome measure—students' individual notebook entries. In a previous study, Hatfield (2011, 2015) employed a similar approach by using ENA to measure the validity of epistemic frames. The analysis correlated the epistemic frame network results with pre/post interviews, but the interview outcome measures were also evaluated using the same epistemic frame approach and thus, limited the model's validity claims. This dissertation study extends Hatfield's work by correlating connected design rationale networks with an outcome measure that was not evaluated using the connected design rationale framework, but rather evaluated by a rubric developed by engineering educators and engineers.

Thus, this study showed that ENA can be used as a validity tool to measure the fidelity of new theoretical and methodological approaches when correlated with alternative outcome measures developed and valued by experts in the field.

Overall, this study extends the research on design thinking and learning by showing that measuring connections among moves and rationale may distinguish between expert and novice levels of thinking across various contexts and in meaningful ways. To clarify, this study is not proposing one specific metric for measuring design thinking that should be applied in future contexts, but rather acts a proof-of-concept to claim that examining connections among moves and rationale—a connected design rationale—could be a promising approach for modeling design thinking.

LIMITATIONS

The study presented in this dissertation has several limitations. First, the ethnographic nature of the investigation of the real-world internship only focused on four participants: two professional engineering experts and two novice student interns. These four participants were used as the basis for the connected design rationale model. Because only four participants were used in a model which examined 15 variables (the co-occurrences of moves and rationale), overfitting may be a concern and the model may not be describing what was claimed in the study and more consequentially, may not fit to new data as expected. Although overfitting exists in models with more variables than observations, there are three reasons that the model developed in this study is still useful. First, this model was motivated by theories and prior work in the field of design thinking and learning sciences which provide strong theoretical support for the variable choices. Second, the variables in this study were chosen based on detailed qualitative, cultural investigations of expert and novice use of moves and rationale which provide strong empirical support for variable choices. Third, the results in this study showed that when the connected design rationale model was applied to new data from the virtual internship, the interpretation remained the same and the model was still able to differentiate between experts and novices. However, as Box (1979) has claimed “all models are wrong but some are useful,” and the model presented in this study may be more useful and have more explanatory power if it measured connections among moves and rationale in a variety of reflective practica settings with larger expert sample sizes, which will be addressed in future work.

A second methodological limitation is that no sensitivity analyses were conducted on the network representations. A sensitivity analysis could provide more insight into whether networks are consistently built over time or if the majority of connections are made at one time point. It could also address the question of whether a learner is making a majority of connections within their own utterances or if she is connecting to other team member’s utterances. However, because this was a preliminary investigation into whether this method could capture salient features of expertise, a thorough sensitivity analysis was not conducted. In future studies, such analyses to test the robustness of the method could be performed in at least two ways. One way would be to construct a model with a random sampling of a student’s chat logs instead of analyzing the entire chat discussion. However, randomly sampling a student’s *utterances* would ignore the context of the utterance within the broader discussion. More technically, the analysis would neglect the connections that a student made from his own utterance to another teammate’s utterance. Thus, to effectively conduct a random sampling of a student’s discourse, the analysis should sample random *window segmentations* which contain the student’s utterance. Another way to test the robustness of the model would be to vary the window utterance size from zero, indicating that a learner is only making connections within their own utterances, to infinity, indicating that a learner is making connections across the entire conversation and not just within a temporal segment. These variations could be analyzed to determine if adjusting the window size affects the results and more specifically, exactly how local connection-making is within this context.

A third limitation addresses the potential confounding variables that were not included in the analyses. One particularly relevant issue is gender identity. For women in male-dominated fields such as engineering, their gender identification as a woman may become more salient (Brewer & Gardner, 1996) and in some cases, have a negative effect on their performance and psychological well-being (Settles, OConnor, & Yap, 2016). Identity salience in engineering has also effected how women interact in collaborative settings. In some cases, women can take on a more subordinate, withdrawn role (Flynn, Savage, Penti, Brown, & Watke, 1991) and can feel isolated or ridiculed (Agogino & Linn, 1992). However, teams with at least two women may experience fewer of these effects (Cordero, DiTomaso, & Farris, 1996; Tonso, 1996) and furthermore, in some cases, when gender composition is ignored, it has little impact on the interactions among team members (Laeser, Moskal, Knecht, & Lasich, 2003). This may suggest that other factors besides gender could be investigated as well, such as leadership skills (Ingram & Parker, 2002), STEM expertise (Flynn et al., 1991), and ethnic or racial identification (Cordero et al., 1996). Thus, examining gender differences as well as other potential confounds in the model remains a task for future work.

Fourth, this study did not investigate question-asking in detail although it was used as a key variable in the analysis to differentiate between experts and novices. In the engineering design education literature, question-asking is a critical topic (Dym et al., 2005). There are various taxonomies of questions asked at varying stages of the design process. Asking clarifying questions can be important during the initial problem identification phase of the design process in which designers begin to define constraints and requests (Dym & Little, 2003). Moreover, Eris (2004) claims that there are two key categories of question-asking which include deep reasoning questions where designers converge to a factual understanding and generative design questions where designers engage in divergent thinking to generate new possibilities. Different types of questions have different objectives and are used in various ways during the design process. For example, deep reasoning questions have been shown to correlate positively with performance in obtaining design solutions (Eris, 2004). In this preliminary study, however, type of question-asking was not differentiated mainly because the move of asking questions was developed from a grounded analysis and thus, was an emergent variable from the data. However, because the results show that connections to the move of asking questions plays a critical role in differentiating experts and novices, it would be beneficial to investigate the forms of question-asking that categorize expert and novice design thinking and how it affects the model presented in this study.

In addition, this study uses an expert-novice approach which has been criticized by some cognitive scientists. Kirschner and colleagues (2006) argue that the ways in which an expert works in his or her domain may not be equivalent to the ways in which one learns the domain, and in turn, expert mental models can significantly differ from those of novices (Dehoney, 1995). However, many of the expert-novice studies that Kirschner and colleagues are referring to have been conducted in lab settings and in turn, have not examined how experts and novices work through ill-structured problems in authentic settings (Dai, 2013). In addition, in many cases the exact same problem was given to both experts and novices and not differentiated for the multiple levels of expertise (see Atman & Turns, 2001; Chi et al., 1981; Cross et al., 1994). In contrast, this study examined ill-structured design work situated in authentic settings, and the design work emerged naturally within the environment in the real-world internship. Similarly, Chinn and colleagues (2000) have developed curricula in ill-structured science domains and have argued that expert mental models are indeed beneficial for learning. However, in future studies, it would be useful to explore multiple models of expertise when working with ill-structured design problems and to not prescribe to the one expert design thinking mental model which was developed in this study.

Next, I describe this model as a web of connections among moves and rationale which assumes no directionality between elements. That is, this approach does not investigate how the structure of connections is affected when rationale follow moves or when moves follow rationale. Although the directionality and order of moves and rationale were not directly investigated in this study, some sections of the results touched on this issue. For example, the high-outcome student from the virtual internship investigation in Part Two, Levi, made connections to the move of experimental testing as shown by his discourse network. The qualitative analysis revealed that Levi both made connections *from* the move of experimental testing to other elements, which was enacted by suggesting experimental tests be conducted, and also *to* the move of experimental testing, which was enacted by responding to someone else’s suggestion for experimental testing. For instance, when Levi’s teammate proposed an experimental move of designing a controlled comparison test, Levi responded with a suggested design choice and a justification based on the performance of the choice. Later in the conversation, the reverse occurred: Levi’s teammate suggested a design choice and a justification to which Levi responded with a description of how to incorporate his teammate’s choice into their existing testing plan. In Levi’s case, incorporating directionality in his model would not have affected his results—he would have still exhibited the discourse connections that were representative of a high-outcome student. However, this is by no means a full investigation of directionality in the connected design rationale model and remains a task for future work.

The final limitation addressed in this paper concerns the nature of connections in the connected design rationale model. This study did not explore the specific, underlying mechanisms of learning that prompted the development of connections within the model. The results suggest that experts and novices in a real-world internship had similar patterns of connections to high and low performing students in a virtual internship, but the results did not explore the reasons why this was case, the stimuli for connection-making, or what the underlying processes were during connection-making in discourse. Nevertheless, this initial study was able to provide evidence that the connected design rationale approach using ENA could in fact capture the salient features of design expertise across settings. Moving forward, this preliminary study sets the stage for further investigations into the causal mechanisms behind connected design rationale learning models.

IMPLICATIONS FOR LEARNING SCIENCES AND ENGINEERING EDUCATION RESEARCH

The work presented in this study suggest an effective approach for modeling and measuring design learning and has several implications for the fields of the learning sciences and engineering design education.

CONNECTED DESIGN RATIONALE AS A COGNITIVE MODEL OF KNOWLEDGE CO-CONSTRUCTION

First, this study provides a working example of measuring and modeling design learning by measuring connections in discourse and thus, provides a proof-of-concept model for connected design rationale. An important conclusion in this study is that design thinking and learning can in fact be measured by examining discourse in situated, authentic design learning environments. This is a significant contribution to the field because, as Atman and colleagues (2008) argue, “Research exists on engineering students’ knowing and thinking, yet how it is enabled through discourse and a community of practice is not well understood.” Thus, the results provide insight into a missing component in engineering design education: a model of how the cognitive design process works when co-constructing knowledge in a social environment. As a result, this work is a promising step towards learning more about design learning and how to model such complex and situated thinking that develops over time.

Connected Design Rationale as a Theoretical Framework for Design Learning

Next, the connected design rationale framework could be a useful theoretical lens for studying design thinking outside of real-world and virtual engineering internships in other environments where design learning occurs. The learning demonstrated in the results is the type of interconnected, complex thinking that is valued in not just engineering design, but in other domains in which design is a central practice, such as architecture, user experience (UX) or user interface (UI) design, or synthetic biology. Additionally, other design disciplines may have other forms of reflective practica in which design learning takes place such as classrooms, studios, or various virtual spaces. Conducting additional work to understand the different patterns of connected design rationale in such contexts can help better define and model design learning across design disciplines and contexts.

Implications for Engineering Design Educators

This dissertation work also has several implications for engineering design educators: (1) the connected design rationale framework provides an approach for educators to develop curricula and assessment tools in terms of identifying connections that students make among moves and rationale, not just that students exhibit these skills in isolation, (2) virtual internships offer authentic simulations of engineering design in the workplace and also assist institutions in scaling up their instruction without sacrificing quality and authenticity, and (3) the integration of virtual internships and ENA provides measurements and assessment models to help instructors effectively guide student learning.

CONNECTED DESIGN RATIONALE AS A PEDAGOGICAL GUIDE

This study proposes connected design rationale as an alternative way for educators to frame their pedagogical and assessment approaches. Traditional engineering instruction consists of “story” problems that have a few preferred solution paths, one correct answer, and are predictive and prescriptive (Jonassen et al., 2006). More recently, institutions have developed innovative curricula which include opportunities for students to engage in authentic, ill-structured engineering design work (Atman et al., 2014; Chesler et al., 2013; Dym et al., 2005). This requires a new approach for instructors to better prepare and assess students to solve such ill-structured design problems. Using the connected design rationale framework, instructors can think ahead about not only what students should do but also how they could justify those actions, and in turn, design the activity to illicit such connected understanding.

When designing rubrics or other assessment methods, an educator can address the relationships among rubric items instead of measuring student skills separately. For example, if one requirement is for students to develop a testing plan, an instructor should provide opportunities for students to provide rationales for such a testing plan either by submitting an engineering notebook, engaging in discussions with teammates, or presenting their work orally. In turn, the instructor can evaluate the strength of arguments that students provide for their design and not simply that a justification was provided. Thus, a connected design rationale provides a way to characterize design learning and can guide educators' pedagogical and measurement choices such that they are considering the relationships among learner's actions and justifications and not simply that students are exhibiting such skills in isolation.

VIRTUAL INTERNSHIPS FOR AUTHENTIC DESIGN LEARNING

This study also suggests that virtual engineering design education is a promising pathway for engineering educators because of two key affordances. First, virtual internships offer theoretically-grounded learning environments in which students can solve simulations of authentic design problems that would otherwise be inaccessible, too risky, or too expensive for students to experience. This characteristic of virtual internships offers a way for students to engage in authentic design work early in their undergraduate careers, which educators researchers have claimed could motivate students to continue in an engineering profession (Arastoopour et al., 2014), enhance their professional engineering learning (Jonassen, 1999), and initiate the student-to-professional transition (Katz, 1993).

Second, virtual internships offer a way for educators to scale up their instruction and provide more students access to quality design instruction. The virtual system facilitates scaling up by automating various actions and activities, which in turn reduces the amount of logistical concerns that may overload an instructor during class. Instructors can then attend to their students in more effective and immediate ways instead of attempting to examine large amounts of information quickly (R. S. Baker, 2016). As the virtual internship system engages with the student directly, the instructor acts more as a mentor or coach as they guide students through the design and problem solving process. As part of this coaching role, instructors must be able to adapt to students' needs, resist the urge to over-teach, and expect that things may not always go as planned (Pavelich, Olds, & Miller, 1995). This change in position could be challenging for some instructors but is necessary for the implementation of innovative engineering design courses in which authentic design work and engaging students in design thinking is a priority (Sheppard & Jenison, 1997). Thus, virtual internships provide opportunities for students to engage with authentic design problems within the simulated world but also to engage in authentic mentorship with their instructors. Of course, this study does not suggest that virtual learning should be the only form of design education—there is clearly value in having students engage with real-world, physical design problems—but that there are significant advantages for institutions to incorporate virtual internships into design programs.

EPISTEMIC NETWORK ANALYSIS FOR DESIGN LEARNING ASSESSMENT

Although the virtual internship environment assists instructors in providing authentic design work for students, instructors may still have difficulty assessing the quality of work that students produce in such process-rich data environments. Such difficulties emerge when students are working in teams and have produced detailed chat logs, are at various points during the design process, or create multiple suitable design prototypes. This study offers a solution for process-rich design assessment by integrating ENA and virtual internships.

Even though ENA was used specifically as a research tool in this study, Atman and colleagues (2008) claim that engineering education research tools may be used as assessment instruments to help guide instruction if adopted in a useful manner. In the context of virtual internships, ENA may be useful for assessment in several ways. First, the virtual internship system tracks large quantities of chat logs, engineering notebooks, and other forms of digital artifacts, which would be difficult and time-consuming for educators to assess manually. As a solution, instructors can use ENA to visualize connections among moves and rationale in student discourse and interpret models of student learning instead of creating the models themselves. Such connected design rationale network models can help instructors to better understand individual and collaborative design practices in their classrooms, which may result in an instructor's decision to reconfigure teams, change the pace of the course, or plan new lessons to facilitate certain patterns of connection-making in students' discourse networks.

The instructor could also choose to be transparent with students about connected design rationale networks created from student data. Instructors could use ENA to build trajectories of student progress and use such visualizations as the basis for conversations with students on improving their design skills, understanding deficiencies in their design reasoning processes, and setting learning goals for future progress, which may help students self-regulate their own learning. In a group setting, instructors can show a team of students the different contributions that each student has made to the team discussions in order to construct a shared mental model of the interaction. This explicit shared mental model may encourage students to set goals for how the team should collaborate in the future and regulate their collaboration more effectively (Soller, Martinez, Jermann, & Muehlenbrock, 2005).

In addition to visualizing large amounts of student data efficiently, connected design rationale network models can support teachers by not only visualizing what students are saying, but also grouping students in ways that are meaningful. Instructors can integrate other forms of assessment they are currently using in their classrooms such as quizzes, participation points, or self-evaluations with students' connected design rationale networks and use ENA to group high and low performing students. In this way, instructors have access to more information as to how a student's performance on a classroom assessment is related to their collaborative design work in the virtual internship. For example, midway through the virtual internship program, an instructor may administer a quiz. Using the grade from the quiz alone only provides the instructor with information on how well or how poorly students performed on that single quiz. However, if the instructor were to use ENA in conjunction with the quiz grades, the instructor could see what patterns of design discourse are related to higher or lower quiz grades and thereby use this information to mentor students in a more informed manner. Thus, using connected design rationale networks together with other assessments may help educators triangulate multiple forms of student work to better intervene with students who are having difficulties and to more effectively guide future learning.

In sum, a connected design thinking approach is valuable for both learning sciences and engineering education research as well as for design educators. Connected design rationale is another step closer towards modeling, measuring, and assessing what we value in modern education—21st century design thinking.

REFERENCES

ABET. (2014). Criteria for Accrediting Engineering.

Adams, R., Daly, S. R., Mann, L. M., & Dall'Alba, G. (2011). Being a professional: Three lenses into design thinking, acting, and being. *Design Studies*, *32*(6), 588–607.

Adams, R., Turns, J., & Atman, C. J. (2003). Educating effective engineering designers: the role of reflective practice. *Design Studies*, *24*(3), 275–294.

Adams, W. K., & Wieman, C. E. (2011). Development and Validation of Instruments to Measure Learning of Expert-Like Thinking. *International Journal of Science Education*, *33*(9), 1289–1312. http://doi.org/10.1080/09500693.2010.512369

Agogino, A. M., & Linn, M. C. (1992). Retaining female engineering students: Will early design experiences help? *National Science Foundation Directions*, *5*(2), 8–9.

Anderson, K. J. B., Courter, S. S., McGlamery, T., Nathans-Kelly, T. M., & Nicometo, C. G. (2010). Understanding engineering work and identity: A cross-case analysis of engineers within six firms. *Engineering Studies, 2*(3), 153–174. http://doi.org/10.1080/19378629.2010.519772

Arastoopour, G., Chesler, N. C., D'Angelo, C. M., Opgenorth, J. W., Reardan, C. B., Haggerty, N. P., … Shaffer, D. W. (2012). Nephrotex: Measuring first year students' ways of professional thinking in a virtual internship. In *American Society for Engineering Education (ASEE)*. San Antonio, TX.

Arastoopour, G., Chesler, N. C., & Shaffer, D. W. (2014). Epistemic persistence: A simulation-based approach to increasing participation of women in engineering. *Journal of Women and Minorities in Science and Engineering*, *20*(3), 211–234.

Arastoopour, G., Chesler, N. C., Shaffer, D. W., & Swiecki, Z. (2015). Epistemic Network Analysis as a Tool for Engineering Design Assessment. In *American Society of Engineering Education*. Seattle, WA.

Arastoopour, G., & Shaffer, D. W. (2013). Measuring Social Identity Development in Epistemic Games. In N. Rummel, M. Kapur, M. Nathan, & S. Puntambekar (Eds.), *The Computer Suppprted Collaborative Learning Conference* (pp. 42–48). Madison, WI.

Arastoopour, G., Shaffer, D. W., Swiecki, Z., Ruis, A. R. R., & Chesler, N. C. N. C. (2016). Teaching and assessing engineering design thinking with virtual internships and epistemic network analysis. *International Journal of Engineering Education*, *32*(3), 1–10.

Arvaja, M., Salovaara, H., Häkkinen, P., & Järvelä, S. (2007). Combining individual and group-level perspectives for studying collaborative knowledge construction in context. *Learning and Instruction*, *17*(4), 448–459. http://doi.org/10.1016/j.learninstruc.2007.04.003

Atkinson, R. (1990, April). Supply and Demand for Scientists and Engineers: A National Crisis in the Making. *Science*, *248*, 425–432.

Atman, C. J., Adams, R., & Turns, J. (2000). Using multiple methods to evaluate a freshmen design course. In *ASEE/IEEE Frontiers in Education Conference*. Kansas City, MO.

Atman, C. J., Chimka, J. R., Bursic, K. M., & Nachtmann, H. L. (1999). A comparison of freshman and senior engineering design processes. *Design Studies*, *20*(2), 131–152.

Atman, C. J., Eris, O., McDonnell, J., Cardella, M. E., & Borgford-Parnell, J. L. (2014). Engineering Design Education. In A. Johri & B. M. Olds (Eds.), *The Cambridge Handbook of the Engineering Education*. New York, NY: Cambridge University Press.

Atman, C. J., Kilgore, D., & McKenna, A. (2008). Characterizing Design Learning: A Mixed-

Methods Study of Engineering Designers' Use of Language. *Journal of Engineering Education*, *97*(3), 309–326.

Atman, C. J., & Turns, J. (2001). Studying Engineering Design Learning: Four Verbal Protocol Studies. In C. M. Eastman, W. M. McCracken, & W. C. Newstetter (Eds.), *Design knowing and learning: cognition in design education* (pp. 37–60). Oxford, UK.

Bagley, E. A., & Shaffer, D. W. (2009). When people get in the way: Promoting civic thinking through epistemic game play. *International Journal of Gaming and Computer-Mediated Simulations*, *1*(1), 36–52.

Bailey, R., & Szabo, Z. (2006). Assessing Engineering Design Process Knowledge. *International Journal of Engineering Education*, *22*(3), 508–518.

Baker, R. S. (2016). Stupid Tutoring Systems, Intelligent Humans Ryan S. Baker. *International Journal of Artificial Intelligence in Education*, *26*(2), 600–614. http://doi.org/10.1007/s40593-016-0105-0

Baker, R. S. J. D., & Yacef, K. (2009). The state of educational data mining in 2009: A review and future visions. *Journal of Educational Data Mining*, *1*(1), 3–17.

Barab, S. A., Hay, K. E., & Yamagata-Lynch, L. C. (2001). Constructing networks of action-relevant episodes: An in situ research methodology. *Journal of the Learning Sciences*, *10*(1&2), 63–112. http://doi.org/10.1207/S15327809JLS10-1-2_5

Boellstorff, T. (2013). Rethinking Digital Anthropology. In H. A. Horst & D. Miller (Eds.), *Digital Anthropology*. New York: Bloomsbury.

Box, G. E. P. (1979). Robustness in the strategy of scientific model building. In R. Launer & G. Wilderson (Eds.), *Robustness in Statistics* (pp. 201–236). New York, NY: Academic Press. http://doi.org/0-12-4381 50-2

Branham, S., Harrison, S., Mccrickard, S., Jones, C., Asimow, M., Archer, B., & Rittel, H. (2007). Making Design Rationale Matter: how design rationale has failed and how it can succeed again. *Human-Computer Interaction*, 1–7.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (1999). *How people learn: Brain, mind, experience, and school*. Washington, D.C.: National Academies Press.

Brewer, M. B., & Gardner, W. (1996). Who Is This "we"? Levels of Collective Identity and Self Representations. *Journal of Personality and Social Psychology, 71*(1), 83–93. http://doi.org/10.1037/0022-3514.71.1.83

Bucciarelli, L. L. (1988). An ethnographic perspective on engineering design. *Design Studies*, *9*(3), 159–168.

Bucciarelli, L. L. (1994). *Designing Engineers*. Cambridge, MA: The MIT Press.

Burge, J., & Brown, D. (1999). *Reasoning with Design Rationale* (Digital Commons @ WPI). Retrieved from http://digitalcommons.wpi.edu/computerscience-pubs/234

Burrell, J. (2012). The Ethnographer's Complete Guide to Big Data: Small Data People in A Big Data World. Retrieved August 1, 2016, from http://ethnographymatters.net/blog/2012/05/28/small-data-people-in-a-big-data-world/

Carnevale, A. P., Smith, N., & Melton, M. (2011). STEM. (C. on E. and the Workforce, Ed.). Georgetown University.

Chesler, N. C., Arastoopour, G., D'Angelo, C. M., Bagley, E. A., & Shaffer, D. W. (2012). Design of professional practice simulator for educating and motivating first-year engineering students. *Advances in Engineering Education*.

Chesler, N. C., Arastoopour, G., D'Angelo, C. M., Bagley, E. A., & Shaffer, D. W. (2013). Design of professional practice simulator for educating and motivating first-year enginnering students. *Advances in Engineering Education*, *3*(3), 1–29.

Chesler, N. C., Ruis, A. R., Collier, W., Swiecki, Z., Arastoopour, G., & Shaffer, D. W. (2015). A novel paradigm for engineering education: Virtual internships with individualized mentoring and assessment of engineering thinking. *Journal of Biomechanical Engineering*, *137*(2), 1–8.

Chi, M., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, *5*(2), 121–152.

Chinn, C. A., Angela, M. O., & Jinks, T. S. (2000). The Structure of Discourse in Collaborative Learning. *The Journal of Experimental Education*, *69*(1), 77–97. http://doi.org/10.1080/00220970009600650

Clancey, W. J. (1997). *Situated cognition*. New York, NY: Cambridge University Press. http://doi.org/10.1002/wcs.1242

Collier, W., Ruis, A. R., & Shaffer, D. W. (2016). Local versus global connection making in discourse. In *International Conference of the Learning Sciences*. Singapore.

Collins, A., Brown, J. S., & Holum, A. (1991). Cognitive apprenticeship: Making thinking visible. *American Educator*, *15*(3), 6–11.

Conklin, E. J., & Yakemovic, K. B. (1991). A Process-Oriented Approach to Design Rationale. *Human-Computer Interaction*, *6*(1991), 357–391.

Cordero, R., DiTomaso, N., & Farris, G. F. (1996). Gender and race/ethnic composition of technical work groups: Relationship to creative productivity and morale. *Journal of Engineering and Technology Management - JET-M*, *13*(3–4), 205–221. http://doi.org/10.1016/S0923-4748(96)01006-5

Creswell, J. W. (2009). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. Los Angeles: Sage.

Creswell, J. W., Hanson, W. E., & Clark, V. L. P. (2007). Qualitative Research Designs: Selection and Implementation. *The Counseling Psychologist*, *35*(2), 236–264. http://doi.org/10.1177/0011000006287390

Cross, N. (1994). *Engineering Design Methods: Strategies for Product Design* (2nd ed.). Chichester, UK: John Wiley & Sons.

Cross, N. (2007). *Designerly Ways of Knowing*. London, UK: Springer-Verlag.

Cross, N., Christiaans, H., & Dorst, K. (1994). Design Expertise Amongst Student Designers. *Journal of Art & Design Education*, *13*(1), 39–56.

D’Angelo, C. M., Shaffer, D. W., & Chesler, N. C. (2011). Undergraduate engineers engaging and reflecting in a professional practice simulation. In *American Society for Engineering Education (ASEE)*. Vancouver, B.C.

Dai, D. Y. (2013). When expert knowledge is not enough: From low roads to high roads. *Invited Speech at Rensselaer the Polytechnic Institute (RPI) Cognitive Science Colloquia*, (September).

Dalkey, N. C., Brown, B. B., & Cochran, S. (1969). *The Delphi Method: An Experimental Study of Group Opinion*. Santa Monica, CA: Rand Corporation.

Dehing, F., Jochems, W., & Baartman, L. (2013). Development of an engineering identity in the engineering curriculum in Dutch higher education: an exploratory study. *European Journal of Engineering Education*, *38*(1), 1–10.

Dehoney, J. (1995). Cognitive Task Analysis: Implications for the Theory and Practice of Instructional Design. In *Annual National Convention of the Association for Educational Communications and Technology*.

diSessa, A. A. (1993). Towards an Epistemology of Physics. *Cognition and Instruction*, *10*(2), 105–225.

diSessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science*, *28*(2004), 843–900. http://doi.org/10.1016/j.cogsci.2004.05.003

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. *Design Studies*, *22*(5), 425–437.

Dorst, K., & Dijkhuis, J. (1995). Comparing paradigms for describing design activity. *Design Studies1*, *16*(2), 261–274.

Downey, G. L., & Lucena, J. C. (2004). Knowledge and professional identity in engineering: code-switching and the metrics of progress. *History and Technology*, *20*(4), 393–420. http://doi.org/10.1080/0734151042000304358

Dreyfus, H. L., & Dreyfus, S. E. (2005). Peripheral Vision Expertise in Real World Contexts. *Organization Studies*, *26*(5), 779–792. http://doi.org/10.1177/0170840605053102

Dym, C. L. (1994). *Engineering Design A Synthesis of Views*. Cambridge, MA: Cambridge University Press.

Dym, C. L., Agogino, A., Eris, O., Frey, D., & Leifer, L. (2005). Engineering design thinking, teaching and learning. *Journal of Engineering Education*, *94*(1), 103–120.

Dym, C. L., & Little, P. (2003). *Engineering Design: A Project-Based Introduction* (2nd ed.). Hoboken, NJ: Wiley.

Eagan, B. R., Rogers, B., Serlin, R., Ruis, A. R., Arastoopour Irgens, G., & Shaffer, D. W. (2017). Can We Rely on IRR? Testing the assumptions of inter-rater reliability. In *Computer Supported Collaborative Learning*. Philadelphia, PA.

Ekwaro-Osire, S., & Orono, P. O. (2007). Design notebooks as indicators of student participation in team activities. *Proceedings - Frontiers in Education Conference, FIE*, *3540*, 18–23. http://doi.org/10.1109/FIE.2007.4418149

Eris, O. (2004). *Effective Inquiry for Innovative Engineering Design*. Norwell, MA: Kluwer Academic Publishers.

Flynn, E. A., Savage, G., Penti, M., Brown, C., & Watke, S. (1991). Gender and Modes of Collaboration in a Chemical Engineering Course. *Journal of Business and Technical Communication*, *5*(4), 444–462.

Freeman, L. C. (2006). *The Development of Social Network Analysis*. Vancouver: Empirical Press.

Friedman, T. L. (2005). *The World is Flat*. New York, NY: Farrar, Straus,and Grioux.

Friedman, T. L. (2016). *Thank You for Being Late: An Optimist's Guide to Thriving in the Age of Accelerations*. New York, NY: Farrar, Straus and Giroux.

Galloway, P. D. (2007). The 21st-Century Engineer: A Proposal For Engineering Education Reform. *Civil Engineering*, *77*(11), 46–52.

Garcia, A. C. B., & Howard, H. C. (2009). Acquiring design knowledge through design decision justification. *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*, *6*(1), 59–71.

Garton, L., Haythornthwaite, C., & Wellman, B. (1997). Studying Online Social Networks. *Journal of Computer-Mediated Communication*, *3*(1).

Gee, J. P. (2004). *Situated Language and Learning: A Critique of Traditional Scooling*. London: Routledge.

Gee, J. P. (2013). *The Anti-Education Era: Creating Smarter Students Through Digital*

Learning. New York, NY: Palgrave Macmillan.

Gee, J. P. (2015). Discourse, small d, Big D. In K. Tracy, C. Ilie, & T. Sanders (Eds.), *The International Encyclopedia of Language and Social Interaction* (pp. 1–5). Wiley-Blackwell.

Gero, J. S. (1998). Conceptual designing as a sequence of situated acts. *Artificial Intelligence in Structural Engineering*, 165–177. http://doi.org/10.1007/BFb0030450

Gero, J. S., & Kannengiesser, U. (2008). An Ontological Account of Donald Schön's Reflection in Designing. *International Journal of Design Sciences and Technologies*, *15*(2), 77–90.

Gero, J. S., & McNeill, T. (1998). An approach to the analysis of design protocols. *Design Studies*, *19*(1998), 21–61.

Gilbuena, D. M., Sherrett, B. U., Gummer, E. S., Champagne, A. B., & Koretsky, M. D. (2015). Feedback on Professional Skills as Enculturation into Communities of Practice. *Journal of Engine*, *104*(1), 7–34. http://doi.org/10.1002/jee.20061

Glaser, B., & Strauss, A. (1967). *The Discovery of Grounded Theory*. Chicago, IL: Aldine Pub Co.

Glesne, C. (1999). *Becoming Qualitative Researchers: An Introduction*. New York: Longman.

Greeno, J. G., & Sande, C. Van De. (2007). Perspectival Understanding of Conceptions and Conceptual Growth in Interaction. *Educational Psychologist*, *42*(1), 9–23. http://doi.org/10.1080/00461520709336915

Harrisberger, L., Heydinger, R., Seeley, J., & Talburtt, M. (1976). *Experiential Learning in Engineering Education*. American Society for Engineering Education.

Hatfield, D. L. (2011). *The right kind of telling: an analysis of feedback and learning in a journalism epistemic game*. *Department of Educational Psychology*. University of Wisconsin-Madison, Madison, WI.

Hatfield, D. L. (2015). The Right Kind of Telling: An Analysis of Feedback and Learning in a Journalism Epistemic Game. *International Journal of Gaming and Computer-Mediated Simulations*, *7*(2), 1–23.

Hatfield, D. L., & Shaffer, D. W. (2006). Press play: Designing an epistemic game engine for journalism. In *ICLS*. Bloomington, IN.

Hsu, W. F. (2014). Digital Ethnography Towards Augmented Empiricism: A New Methodological Framework. *Journal of Digital Humanities*, *3*(1).

Ingram, S., & Parker, a. (2002). *Gender and Modes of Collaboration in an Engineering Classroom: A Profile of Two Women on Student Teams*. *Journal of Business and Technical Communication* (Vol. 16). http://doi.org/10.1177/1050651902016001002

Jacobson, M. J., & Wilensky, U. (2015). Complex Systems in Education: Scientific and Educational Importance and Implications for the Learning Sciences. *The Journal of the Learning Sciences*, *15*(1), 11–34.

Jiang, Y. H., Wai, S., & Lee, Y. I. N. (2015). Analyzing student and employer satisfaction with cooperative education through multiple data sources. *Journal of Cooperative Education*, *16*(4), 225–240.

Johri, A. (2010). Situated Engineering in the Workplace. *Engineering Studies*, *2*(3), 151–152. http://doi.org/10.1080/19378629.2010.536427

Johri, A. (2011). Sociomaterial bricolage : The creation of location-spanning work practices by global software developers. *Information and Software Technology*, *53*(9), 955–968. http://doi.org/10.1016/j.infsof.2011.01.014

Johri, A., & Olds, B. M. (2011). Situated Engineering Learning: Bridging Engineering Education Research and the Learning Sciences. *Journal of Engineering Education*, *100*(1), 151–185.

http://doi.org/10.1002/j.2168-9830.2011.tb00007.x

Jonassen, D. H. (1999). Designing Constructivist Learning Environments. In *Instructional design theories and models: A new paradigm of instructional theory* (pp. 215–239).

Jonassen, D. H. (2000). Towards a Design Theory of Problem Solving. *Educational Technology Research and Development*, *48*(4), 63–85.

Jonassen, D. H., Strobel, J., & Beng Lee, C. (2006). Everyday Problem Solving in Engineering: Lessons for Engineering Educators. *Journal of Engineering Education*, *95*(2), 139–151.

Kane, M. T. (2006). Validation. *Educational Measurement*, *4*(2), 17–64.

Katz, S. M. (1993). The Entry-Level Engineer : Problems in Transition from Student to Professional. *Journal of Engineering Education*, *82*(3), 171–174.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Experiential , and Inquiry-Based Teaching Work : An Analysis of the Failure of Constructivist , Discovery , Problem-Based , Experiential , and Inquiry-Based Teaching. *Educational Psychologist*, *41*(2), 75–86. http://doi.org/10.1207/s15326985ep4102

Knight, S., Arastoopour, G., Shaffer, D. W., Buckingham Shum, S., & Littleton, K. (2014). Epistemic Networks for Epistemic Commitments. In *Proceedings of the International Conference of the Learning Sciences*. Boulder, CO.

Laeser, M., Moskal, B. M., Knecht, R., & Lasich, D. (2003). Engineering Design : Examining the Impact of Gender and the Team ' s Gender. *Journal of Engineering Education*, (January), 49–56. http://doi.org/10.1002/j.2168-9830.2003.tb00737.x

Lawson, B. (2005). *How Designers Think: The Design Process Demystified* (Fourth Edi). Oxford, UK: Elsevier.

Lee, J. (1997). Design Rationale Systems: Understanding the Issues. *IEEE Intelligent Systems*, *12*(3), 78–85.

Lee, J., & Lai, K.-Y. (1991). What's in Design Rationale? *Human-Computer Interaction*, *6*, 251–280.

Linn, M. C. (1995). Designing Computer Learning Environments for Engineering and Computer Science: The Scaffolded Knowledge Integration Framework. *Journal of Science Education and Technology*, *4*(2), 103–126.

Linn, M. C. (2006). The Knowledge Integration Perspective on Learning and Instruction. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 243–264). New York, NY: Cambridge University Press.

Linn, M. C., Eylon, B. S., & Davis, E. A. (2004). The knowledge integration perspective on learning and instruction. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 29–46). Mahwah, NJ: Lawrence Erlbaum Associates.

Marples, D. L. (1961). The decisions of engineering design. *IRE Transactions of Engineering Management*, *8*(2), 55–71.

McCall, R., & Burge, J. (2016). Untangling wicked problems. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *30*(2), 200–210. http://doi.org/10.1017/S089006041600007X

McCall, R., Fischer, G., & Morch, A. (1989). Supporting Reflection-in-Action in the Janus Design Environment. In *CAAD Futures Digital Proceedings* (pp. 247–259).

Messick, S. (1995a). Standards of validity and the validity of standards in performance assessment. *Educational Measurement: Issues and Practice*, 5–8. http://doi.org/10.1111/j.1745-3992.1995.tb00881.x

Messick, S. (1995b). Validity of Psychological Assessment. *American Psychologist, 50*(9), 741–749. http://doi.org/10.1037//0003-066X.50.9.741

Mislevy, R. J., & Steinberg, L. (2003). A four-process architecture for assessment delivery, with connections to assessment design. Los Angeles: National Center for Research on Evaluation, Standards and Student Testing (CRESST).

Mislevy, R. J., Steinberg, L. S., & Almond, R. G. (2003). On the Structure of Educational Assessments. *Measurement: Interdisciplinary Research & Perspective*, *1*(1), 92–101.

Monahan, T., & Fisher, J. A. (2014). Strategies for Obtaining Access to Secretive or Guarded Organizations. *Journal of Contemporary Ethnography*, *44*(6), 709–736. http://doi.org/10.1177/0891241614549834

Nash, P., & Shaffer, D. W. (2008). Mentor modeling: The internalization of modeled professional thinking in an epistemic game. In *ICLS* (pp. 269–276). Chicago, IL: International Society of the Learning Sciences.

Nash, P., & Shaffer, D. W. (2013). Epistemic trajectories: Mentoring in a game design practicum. *Instructional Science, 41*(4), 745–771.

National Academy of Engineering. (2004). *The Engineer of 2020: Visions of Engineering in the New Century*. Washington, D.C.: The National Academies Press.

National Academy of Engineering. (2008). *Grand Challenges for Engineering* (Vol. 37). Washington, D.C.: National Academies Press.

National Research Council. (1996). *National Science Education Standards*. National Academies Press.

National Research Council. (2001). *Know What Students Know: The Science and Design of Educational Assessment*. (J. W. Pellegrino, N. Chudowsky, & R. Glaser, Eds.). Washington, DC: National Academy Press.

National Science Foundation. (1993). *Science and Engineering Indicators 1993*. Washington, D.C.

National Science Foundation. (2014). *Science and Engineering Indicators 2014*. Washington, DC.

Noble, D., & Rittel, H. W. . (1988). Issue-Based Information Systems for Design. *Computing in Design Education [ACADIA Conference Proceedings]*, 275–286. Retrieved from http://cumincad.scix.net/cgi-bin/works/Show?ca71

O’Connor, K., Amos, D., Bailey, T., Garrison, L., Jones, M., Lichtenstein, G., … Stevens, R. (2007). Sponsorship: Engineering’s tacit gatekeeper. In *American Society for Engineering Education Annual Conference*. Honolulu, HI.

Palincsar, A., & Lehrer, R. (2004). Introduction to Special Issue: Investigating Participant Structures in the Context of the Context of Science Instruction. *Cognition and Instruction*, *22*(4), 389–392.

Papalambros, P. Y., & Georgiopoulos, P. (2006). A Designer’s View to Economics and Finance. In *Decision Making in Engineering Design* (pp. 187–202). ASME Press.

Pavelich, M. J., Olds, B. M., & Miller, R. L. (1995). Real-world problem solving in freshman-sophomore engineering. *New Directions for Teaching and Learning, 61*, 45–54. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/tl.37219956108/abstract

Ralph, E., Walker, K., & Wimmer, R. (2009). Praccticum-Education Experiences: Post-Interns’ View. *International Journal of Engineering Education*, *25*(1), 122–130.

Razzouk, R., & Shute, V. (2012). What Is Design Thinking and Why Is It Important? *Review of Educational Research*, *82*(3), 330–348.

Rittel, H. W. J. (1987). The Reasoning of Designers. In *Congress on Design Planning and Design Theory*. Boston, MA.

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a General Theory of Planning. *Policy Sciences*, *4*(2), 155–169.

Rowe, G., & Wright, G. (1999). The Delphi technique as a forecasting tool: issues and analysis. *The International Journal of Forecasting*, *15*, 353–375.

Saucerman, J., Ruis, A. R., & Shaffer, D. W. (2017). Automating the Detection of Reflection-on-Action. *Journal of Learning Analytics*, *In press*.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. New York: Basic Books.

Schön, D. A. (1984). Problems , frames and perspectives on designing. *Design Studies*, *5*(3), 132–136.

Schön, D. A. (1987). *Educating the reflective practitioner: Toward a new design for teaching and learning in the professions*. San Francisco: Jossey-Bass.

Schön, D. A. (1988). Designing: Rules, types and worlds. *Design Studies*, *9*, 181–190.

Schön, D. A., & Wiggins, G. (1992). Kinds of seeing and their functions in designing. *Design Studies*, *13*(2), 135–156. http://doi.org/10.1111/j.1467-8691.1992.tb00031.x

Settles, I. H., OConnor, R. C., & Yap, S. C. Y. (2016). Climate Perceptions and Identity Interference Among Undergraduate Women in STEM: The Protective Role of Gender Identity. *Psychology of Women Quarterly*, *40*(4), 488–503. http://doi.org/10.1177/0361684316655806

Seymour, E., & Hewitt, N. M. (1997). *Talking About Leaving: Why Undergraduates Leave the Sciences*. Boulder, CO: Westview Press.

Shaffer, D. W. (2004). Epistemic frames and islands of expertise: Learning from infusion experiences. In Y. Kafai, W. A. Sandoval, N. Enyedy, A. S. Nixon, & F. Herrera (Eds.), *Proceedings of the Sixth International Conference of the Learning Sciences* (pp. 473–480). Santa Monica, CA: Erlbaum.

Shaffer, D. W. (2005a). Epistemography and the Participant Structures of a Professional Practicum: A story behind the story of Journalism 828. University of Wisconsin-Madison, Wisconsin Center for Education Research.

Shaffer, D. W. (2005b). *Epistemography and the Participant Structures of a Professional Practicum: A Story Behind the Story of Journalism 828* (Wisconsin Center for Educational Research No. 2005–8).

Shaffer, D. W. (2005c). *Multisubculturalism: Computers and the end of progressive education* (Vol. 2005). University of Wisconsin-Madison, Wisconsin Center for Education Research.

Shaffer, D. W. (2006). Epistemic frames for epistemic games. *Computers and Education*, *46*(3), 223–234.

Shaffer, D. W. (2007a). *How Computer Games Help Children Learn*. New York: Palgrave.

Shaffer, D. W. (2007b). Learning in Design. In R. A. Lesh, J. J. Kaput, & E. Hamilton (Eds.), *Foundations for the Future in Mathematics Education* (pp. 99–126). Mahweh, NJ: Lawrence Erlbaum Associates.

Shaffer, D. W. (2012). Models of situated action: Computer games and the problem of transfer. In C. A. Steinkuehler, K. D. Squire, & S. A. Barab (Eds.), *Games learning, and society: Learning and meaning in the digital age* (pp. 403–433). Cambridge, UK: Cambridge University Press.

Shaffer, D. W., Borden, F., Srinivasan, A., Saucerman, J., Arastoopour, G., Collier, W., …

Frank, K. A. (2015). *The nCoder: A Technique for Improving the Utility of Inter-Rater Reliability Statistics* (Epistemic Games Group Working Paper No. 2015–1).

Shaffer, D. W., Collier, W., & Ruis, A. R. (2016). A Tutorial on Epistemic Network Analysis: Analyzing the Structure of Connections in Cognitive, Social, and Interaction Data. *Journal of Learning Analytics*, *3*(3), 9–45.

Shaffer, D. W., Hatfield, D., Svarovsky, G., Nash, P., Nulty, A., Bagley, E. A., … Mislevy, R. J. (2009). Epistemic Network Analysis: A prototype for 21st century assessement of learning. *The International Journal of Learning and Media*, *1*(1), 1–21.

Shaffer, D. W., & Ruis, A. R. (2017). Epistemic network analysis: A worked example of theory-based learning analytics. In *Handbook of Learning Analytics and Educational Data Mining* (p. in press).

Sheppard, S. D., & Jenison, R. (1997). Examples of Freshman Design Education. *International Journal of Engineering Education, 13*(4), 248–261.

Sheppard, S. D., Macatangay, K., Colby, A., & Sullivan, W. M. (2009). *Educating Engineers*. San Francisco, CA: Jossey-Bass.

Sheppard, S. D., Pellegrino, J. W., & Olds, B. M. (2008). On Becoming a 21st Century Engineer. *Journal of Engineering Education*, *97*(3), 231–234.

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass Correlations: Uses in Assessing Rater Reliability. *Psychological Bulletin*, *86*(2), 420–428.

Shum, S. B., & Hammond, N. (1994). Argumentation-Based Design Rationale: What Use at What Cost ? *International Journal of Human-Computer Studies*, *40*(4), 603–652.

Shute, V. J., Ventura, M., Zapata-rivera, D., & Bauer, M. (2009). Melding the power of serious games and embeded assessment to monitor and foster learning flow and grow. In U. Ritterfeld, M. Cody, & P. Vorderer (Eds.), *Serious games: Mechanisms and effects* (pp. 295–321). Mahwah, NJ: Routledge, Taylor, and Francis. http://doi.org/10.4324/9780203891650

Siebert-Evenstone, A. L., Arastoopour, G., Collier, W., Swiecki, Z., Ruis, A. R., & Shaffer, D. W. (2016). In Search of Conversational Grain Size: Modeling Semantic Structure using Moving Stanza Windows. In *International Conference of the Learning Sciences*. Singapore.

Silva, E. (2008). *Measuring Skills for the 21st Century*. Washington, D.C.

Simon, H. A. (1996). *The sciences of the artificial* (3rd ed.). Cambridge, MA: MIT Press.

Snyder, T. D., Dillow, S. A., & Hoffman, C. M. (2009). *Digest of Education Statistics 2008*. *National Center for Education Statistics*.

Soller, A., Martinez, A., Jermann, P., & Muehlenbrock, M. (2005). From Mirroring to Guiding: A Review of State of the Art Technology for Supporting Collaborative Learning. *International Journal of Artificial Intelligence in Education*, *15*, 261–290.

Stevens, R., O'Conner, K., Garrison, L., Jocunus, A., & Amos, D. (2008). Becoming an Engineer: Toward a Three Dimensional View of Engineering Learning. *Journal of Engineering Education*, *97*(3), 355–368.

Suchman, L. A. (1987). *Plans and situated actions: the problem of human-machine communication*. New York, NY: Cambridge University Press.

Suchman, L. A. (2000). Organizing Alignment: A Case of Bridge-building. *Organization*, *7*(2), 311–327.

Svarovsky, G. N. (2011). Exploring Complex Engineering Learning Over Time with Epistemic Network Analysis. *Journal of Pre-College Engineering Education Research (J-PEER)*, *1*(2), 4.

Tener, R. K., Winstead, M. T., & Smaglik, E. J. (2001). Experiential Learning from Internships in Construction Engineering. In *American Society for Engineering Education Conference* (pp. 4889–4920). Albuquerque, NM.

Tonso, K. L. (1996). Student learning and gender. *Journal of Engineering Education*, *85*(2), 143–150.

Trevelyan, J. (2010). Mind the Gaps: Engineering Education and Practice. *Proceedings of the 2010 AaeE Conference, Sydney*, (April), 383–390. Retrieved from http://aaee.com.au/conferences/AAEE2010/PDF/AUTHOR/AE100035.PDF

Ulrich, K. T., & Eppinger, S. D. (2011). *Product Design and Development*. New York: McGraw-Hill.

Vinck, D. (2003). *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology*, *8*(1), 3–19.

Wiltschnig, S., Christensen, B. T., & Ball, L. J. (2013). Collaborative problem-solution co-evolution in creative design. *Design Studies*, *34*(5), 515–542. http://doi.org/10.1016/j.destud.2013.01.002

Zoltowski, C. B., Oakes, W. C., & Cardella, M. E. (2012). Students' Ways of Experiencing Human-Centered Design. *Journal of Engineering Education*, *101*(1), 28–59.