Diagramming Prior Knowledge in the Classroom: A Case Study

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ABSTRACT

Engaging the student's prior knowledge is considered by educational researchers to be an important part of constructing a strong foundation for new learning. Diagrams are one technique used in the classroom. Jill Larkin and Herbert Simon described the computational advantages of diagrams over text when used to communicate information in their 1987 article entitled "Why a Diagram is (Sometimes) Worth Ten Thousand Words."

This case study describes a novel abstract diagramming technique facilitated in four separate university classroom settings. Using paper and crayons, the students created three diagrams that represented the externalization of their unconscious perceptions of their own prior knowledge. The study illustrates how differences in prior knowledge can be visualized using diagrams with greater speed in less time than the traditional use of text-based descriptions.

The use of the abstract diagramming technique led to an unexpected finding. The student diagrams were shown to contain a hidden conceptual topology, one that is described by Egenhofer in his 1991 article entitled "Reasoning About Binary Topological Relations." This topology is recommended as a framework for structuring and facilitating student collaboration and sharing of prior knowledge and new learning.

The present study recommends the diagramming technique as the basis for the establishment of a standard diagram research framework that can be used across multiple research disciplines and subject domains. This dissertation describes a domain-general abstract diagram technique that can be adapted for domain-specific subjects and made operational using basic materials (paper and crayons). The study also describes the instructors' responses to questions about the diagram technique used in their classes. The case study offers recommendations for future diagram research.

Dedication

Killed in South Korea, March 24th, 1984, Helicopter Crash

Captain S.J BURLEY
Captain J.H. HOUSTON
Sergeant D.C. HIGGINS
Corporal J.J ACQUISTO
Gunnery Sergeant Richard M. BJECKO
Staff Sergeant John R. LIDDLE
Sergeant Kevin J. MUGOODWIN
Corporal Tim B. KELLY
Corporal Kenneth B. CROSBY
Lance Corporal Bradley A. MCCOMAS
Lance Corporal Daniel B. ZINCK
Lance Corporal Fernando ROSALEZ Jr.
Private First Class James T. ROONEY
Private First Class Edward C. FERRELL
Private First Class William A. SOLES
Private First Class Anthony S. DUGAS
Lance Corporal Herman L. OSCEOLA 262
Private First Class John M. ANDREWS III
Second Lieutenant JYE KWON KOO
Staff Sergeant JAE KEUN SIM
Staff Sergeant SOON SOK KIM
Staff Sergeant HWI MOON KIM
Sergeant MOON JOO OH
Sergeant SEONG YI LEE
Sergeant TAE YOUNG KIM
Sergeant SOON KI LEE
Corporal YOON NAM LEE
Corporal YOUNG CHUL SIN
Private DOO SONG CHANG

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CHAPTER ONE - INTRODUCTION

The classroom in today's university environment is very different from the setting of even just a few years ago. Students have new information at their fingertips thanks to innovations targeting the internet, mobile phones, and the wireless web. Engaging the student's prior knowledge is considered by researchers and academics to be an important instructional strategy when laying the foundation for new learning in the classroom (Ambrose, Bridges, Lovett, DiPietro, & Norman, 2010; Bransford, 2000; Harris, Breier, & Wihak, 2011; Hattie, 2009). This context presents a unique challenge for the university instructor.

In this case study university students were observed creating diagrams of prior knowledge using an abstract diagram elicitation technique. The technique was facilitated in four different classroom settings. My research describes how the diagramming technique was made operational, how the student-generated diagrams revealed a hidden topology of shapes that supported a framework for sharing and collaboration, and how the instructors responded to their experience of sponsoring the diagram elicitation technique. Suggestions for future research are included with a focus on the use of abstract diagrams in the classroom and in practice.

Background

I first encountered the value of using diagrams to communicate prior knowledge while serving in the United States military. My squadron was training to fly with night vision goggles, but the underlying concepts of how the technology worked were not included in the instructional materials. This lack of training in the operational limitations of the technology led to a tragic accident, killing 29 U.S. Marines (Powers, 1984). The basic concepts and risks regarding night vision goggle flying while piloting helicopters had been published a decade earlier, but never included in the training program (Sanders, Kimball, Frezell, & Hofmann, 1975). The simple, abstract diagrams contained in the publication were quite effective in communicating the limitations of the night vision goggle technology.

My studies in graduate school at the University of Southern California included a review of a paper published in the cognitive science field related to the use of node-link diagrams and pattern matching (Larkin, McDermott, Simon, & Simon, 1980). This paper came to mind years later while preparing for a class project in facilitating adult learning at Virginia Tech (Klunk, 2009). I discovered an updated work by the previous authors (Larkin & Simon, 1987) during my research for the class project. The researchers described the unique advantages of using diagrams as an external representation when communicating information in contrast with using text.

My background in systems engineering and data modeling complemented my research in the use of diagrams. The development of computer system architecture is based on the use of entity-relationship (E-R) diagrams to model systems of large organizations (P. Chen, 1975). These types of diagrams function as conceptual models of how organizations operate and how they manage their resources. By combining my data modeling experience with the ideas proposed by Larkin and Simon (1987), I conceived of student-generated diagrams as a possible technique for eliciting prior knowledge.

The idea of using diagrams as the focal point of the class project was reinforced by my experience taking three other graduate courses in the spring semester of 2009 (Boucouvalas, 2009; L. Morris, 2009; Renard, 2009). The course subjects included adult learning theory and practice, small group theory and practice, and consulting in human systems theory and practice.

During the semester, my experience attending the in-person classes, and participating in the peer-to-peer interactions, confirmed my personal belief that the prior knowledge of my fellow students' conceptualization about adult learning theories varied widely. Considering the instructors' challenge of engaging prior knowledge led me to further investigate possible diagram techniques for use in my project. None of the research I surveyed addressed diagrams as a technique to elicit student prior knowledge. This gap in the research led me to construct a diagramming prototype and experimental technique for the class project.

My design of the experimental technique created for the class project required the students to create three diagrams using butcher block paper, glue sticks, and cut-outs of geometric shapes. I created three questions as a way of prompting the students for a response when creating their diagrams of prior knowledge. The questions were based on findings by a National Research Council project that summarized key recommendations for teachers when engaging students in new learning (Bransford, 2000). The elicitation questions were designed to elicit the student's general prior knowledge of conceptualizations about how the world worked. I have reproduced the questions below.

1) How does the world work?

2) How do you store that information in memory?

3) How do you monitor your own learning when things change in the real world?

Each student was instructed to use the materials to create an answer to each of the three questions, all in the form of diagrams, made from the geometric shape pieces, and glued to the butcher block paper. At the conclusion of the diagram generation phase of the exercise, the students provided verbal explanations of what their diagrams were meant to communicate. The objective of the exercise was to show how their worldviews differed when represented visually. There was a general surprise and curiosity among the students about how effective the technique was in representing personal conceptualizations of general knowledge. It was this experience that led to my proposal for this dissertation. This case study was designed to further explore how to make diagram elicitation operational in the classroom, as a technique to elicit the student's prior knowledge, within a domain subject area.

Statement of the Problem

The college Professor is faced with teaching a student population that is diverse and represented by a broad range of cultural backgrounds, education, and personal experiences. Engaging the student's prior knowledge is also challenging in an environment constrained by time and resources, much of which is dedicated to new learning (Ambrose et al., 2010). How can instructors engage student prior knowledge in a way that helps create a foundation for new learning, collaboration, and sharing?

The Gap in the Literature

There is a significant body of literature on diagrams, prior knowledge, and the assessment of student knowledge. On closer inspection, the range of topics in the field of diagram research spans many disciplines, all of which include varying definitions. For example, Purchase (2014, p. 59) offers a definition of diagram as "taken to mean a composite set of marks (visual elements) on a two-dimensional plane that, when taken together, represent a concept or object in the mind of the viewer.” I selected the Larkin and Simon (1987, p.68) definition of diagram as a “data structure in which information is indexed in a two-dimensional location” for use in this case study.

In a similar fashion, the definition of prior knowledge varied across disciplines (Falk & Dierking, 1995). The most widely accepted view in the educational psychology field of prior knowledge is that knowledge is “what the learner already knows” (Ausubel, 1968). Educational researchers have continued to further classify prior knowledge into three sub-categories, described as declarative, procedural, and conceptual knowledge (Duffy & Jonassen, 1993; Jonassen, Beissner, & Yacci, 1993). Conceptual knowledge is considered by educational researchers as the foundation upon which all other knowledge is grounded (Dochy, Segers, & Buehl, 1999; Eppler, 2006; Jonassen, 2004; Sowa, 1984; Vosniadou, 2008). Based on this orientation to knowledge in the educational research field, I selected *conceptual* knowledge as the focus of my elicitation technique.

I searched the literature for detailed information about how to leverage the advantages inherent in diagrams as described by Larkin and Simon (1987). I was specifically looking for diagram research that characterized diagrams as more abstract and consistent with the node-link definition I had selected. I could not locate research that described techniques for using abstract diagrams to elicit prior knowledge of concepts in a subject area. I turned to a review of dissertations as a possible source of information regarding the use of diagrams as a technique for eliciting student-generated representations of prior knowledge. None of the results met the requirements for my search.

The design of research using visual data is seeing renewed interest in other areas. Euler diagrams were implemented as a technique to visualize concepts (J. Burton, Stapleton, Howse, & Chapman, 2014). Diagrams were used to study meaning in mathematics (Dimmel & Herbst, 2015). Research explored the use of diagrams in professional practice (Giardino, 2013). Political scientists used diagrams in qualitative studies (Mahoney & Vanderpoel, 2015). Diagrams were used in design studies and the cognitive sciences (Nickerson et al., 2013; Tversky, 2011; Tversky & Kessell, 2014; Tversky & Suwa, 2009). Diagrams were used in research to understand how exceptional children learn (Poch, van Garderen, & Scheuermann, 2015; van Garderen & Scheuermann, 2015; van Garderen, Scheuermann, & Jackson, 2013). Diagrams were used in the health sciences field to collect data in qualitative research settings (Burchett, Umoquit, & Dobrow, 2011; Umoquit, Tso, Burchett, & Dobrow, 2011; Umoquit, Tso, Vargas-Atkins, O'Brien, & Wheeldon 2013).

The most comprehensive studies of elicitation techniques were consistent in their orientation to abstract diagrams. Research focused on abstract diagrams was minimal. The use of student-generated, abstract diagrams to elicit prior knowledge of conceptual understanding was a gap in the literature (A. Burton, Shadbolt, Rugg, & Hedgecock, 1990; Cooke, 1994; Dieste & Juristo, 2011; Gavrilova, Leshcheva, & Rumyantseva, 2011; Jones, Miles, & Read, 1996; Marshall & Gordon, 2011; Purchase, 2014; Umoquit et al., 2013).

Purpose and Significance

The purpose of this case study was to describe a diagram technique that was made operational for use as an elicitation of prior knowledge technique using student-generated diagrams. This study describes my observations and interpretation of the instructors' responses to the diagram elicitation exercises conducted in their classrooms.

This case study is significant because the method explores a technique for eliciting prior knowledge in the classroom that places minimal requirements on the students, instructors, or researchers when learning to use abstract diagrams as a communications tool. The diagram technique links prior diagram research to new research by using a novel, but common visual language (geometric shapes) situated in a conceptual space (Gardenfors, 2000, 2014). The study offers conceptual change theorists a tool for conducting studies using diagrammatic data collected from multiple dimensions (Vosniadou, 2008, 2012). This study adds to the growing body of research in the field of spatial intelligence and spatial cognition through the contribution of a general technique for eliciting domain-specific external representations (Waller & Nadel, 2013). It describes an accessible and easy-to-adapt technique for studying the differences in the embedded binary relations of conceptual topology found in cognitive spatial models (Leighton & Gierl, 2007, 2011).

Research Design

The research was presented in the form of a case study, considered here to be the best approach to describe my observations of the students and instructors in the four different classroom settings. Yin (2009) recommends a project plan orientation to the tasks associated with designing, preparing, collecting, analyzing, sharing, and reporting. This approach best supported the various timelines, logistics, and coordination required for data collection that took place across four campus locations. The hierarchical order of the student data in the diagram artifacts was based on the unit of analysis construct suggested by Yin (2009). This orientation provided the top-down organization for managing the data collection tasks and resources.

The structure of organizing the research data from the bottom-up was based on the integrative node-link structure proposed by Maxwell (2013). This made it possible to easily organize, visually contrast, and compare the individual student diagram topology across the students, classes, and subject levels. The Maxwell topology and conceptual framework placing the research questions as central to the case study aligned to the concepts of geometric topology and abstraction suggested by Egenhofer (1991).

The Conceptual Framework

This study is positioned within the disciplines of adult learning (Knowles, Holton, & Swanson, 2005) and human development (Deacon, 1998; Staats, 2012). The research is based on constructivism as the conceptual framework (Fosnot, 1996). Early discourse in philosophy informed our inquiry into learning and development beginning during the time of Plato and Aristotle. The origins of modern educational psychology and constructivism were based on the works of Dewey (1916), Piaget (1954), and Vygotsky (1978). The work by Ausubel (1960) in developing advanced organizers provided a grounded approach to creating physical artifacts that represented prior knowledge and new learning. Contributions from computer science, artificial intelligence, and the cognitive sciences accelerated the introduction of constructivism to educators inside and outside the classroom (R. Anderson, Spiro, & Montague, 1977; Newell & Simon, 1972; Novak & Gowin, 1984; Sowa, 1984). This stream of research led to public debates in the field regarding the efficacy of the various constructivist approaches to learning in the classroom and were detailed in the work by Tobias and Duffy (2009).

The evolution of constructivist theories in recent years positions students in the classroom as occupying a mental space wherein they construct conceptual knowledge (Fiorini, Gardenfors, & Abel, 2014; Gardenfors, 2014; Gardenfors & Zenker, 2013; Warglien & Gardenfors, 2013).

The diagram technique brought this mental space to life by grounding the elicitation of conceptual knowledge in the form of crayons and paper. This process placed the study as one more contribution to the catalogue of constructivist approaches to knowledge creation in the classroom (Buckley & Waring, 2013; Cromley, Bergey, et al., 2013; Cromley, Perez, et al., 2013; Novick & Catley, 2014; van Garderen et al., 2013).

Research Questions

The research questions were designed to position the case study as a report of my observations of students using geometric shapes to diagram their prior knowledge in four different classroom setting. The research questions provided a structure to analyze the diagram differences, investigate how students could use the diagrams in a group setting, and follow up with the instructors regarding their experience in observing the elicitation technique. The research questions are provided below.

- How can abstract diagrams constrained by domain-general, geometric shapes be made operational in a diagram elicitation technique, and thereby make prior knowledge of students accessible visually within the context of a domain-specific classroom setting?
- How can the diagrams offer learners the opportunity to collaborate and share diagrams that could lead to the creation of shared prior knowledge?
- To what extent does the instructor perceive the diagram technique to be useful as a tool for eliciting prior knowledge at the individual level, and at the group level?

Assumptions and Limitations

This dissertation described the facilitation and elicitation of student-generated diagrams based on a technique that was created for a class project. The research questions provided the basis for situating the student-generated diagrams as a visual technique for representing student prior knowledge. The diagram technique described in this study was designed to align with the Larkin and Simon research framework of using node-link structures to illustrate the differences in the search, recognition, and inferences possible when using a topology of visual indexes (Larkin & Simon, 1987). A general assumption was made in the study that students would be familiar with the basic use of paper and crayons in the context of creating triangles, squares, and circles. Beyond that prior knowledge, the study did not infer or assume any prior knowledge by the student regarding abstract diagramming knowledge, skills, or abilities.

This study did not address the elicitation of diagrams using *concrete* visual representations given the existing body of literature noted in this area by Purchase (2014). It did not seek to collect and interpret data with the goal of inferring diagram meanings or semantics of the student-generated diagrams, although this area is a new and emerging area in the diagram research (Galantucci, 2010; Gardenfors, 2014). The possible combinations and permutations of diagram shapes, topology, and relations are theoretically infinite (Papadimitriou & Steiglitz, 1982). The study did not seek to explore and document methods for creating subject-specific lexicons, vocabularies, or referent diagrams in a given domain of study for this reason.

Definition of Terms

The key terms are defined for the reader in this section. The terms are in such general use across domains that they can be easily misinterpreted. The definitions are provided within the context of how they are used in this study and not meant to extend these interpretations or meanings to other research domains.

Diagram is defined within the context of this study as a visual image that is constructed through the physical process of locating a point and a connecting line on a drawing canvas, in this case, a piece of blank paper (Larkin & Simon, 1987).

The diagram is further constrained by the limitation that excludes embellishments, annotations, labels, numbers, and other special notations, making the diagrams *abstract* in contrast to *concrete* diagrams (Purchase, 2014).

The node-link, point-line connections must be constructed in such a way as to create the geometric shapes of triangles, squares, or circles. These are the only shapes allowed in the diagram created by the students. This rule or specification is referred to in the literature as a *shape grammar* (Stiny, 1975).

The drawing canvas is embodied in the form of a blank sheet of paper measuring 8.5 by 11 inches. The diagramming utensils are a random collection of colored crayons chosen by the students from a large selection stored in a box. The materials make it possible for students to construct external representations of internal thought processes in a location referred to by cognitive science researchers as a *conceptual space* (Gardenfors, 2000, 2014).

Domain as used in this case study refers to a body of knowledge that is normally identified by a subject label such as physics, economics, biology, and mathematics (Novick, 2006). *Domain-specific* is meant to communicate that a noun or adjective is specific to one domain when compared to other domains. *Domain-general* is meant to communicate or describe a noun or adjective that can be applied across different domains (Novick, 2006).

Knowledge describes the collection of facts, processes, information, data, skills, and abilities associated with a subject area (Sowa, 1984). In turn, it follows that *prior knowledge* is the collective knowledge a student brings with them to the classroom that they have acquired through education, training, and life experience (Dochy et al., 1999). The study adopts the further breakdown of prior knowledge into *declarative, procedural,* or *conceptual* types of knowledge (Jonassen, 2006; Jonassen et al., 1993; Jonassen & Strobel, 2006).

Declarative knowledge refers to the collection of facts, statements, and principles that describe a subject or specific domain (Jonassen, 2004).

Procedural knowledge refers to the collection of processes, methods, and activities that describe how to act upon or with facts, statements, principles, or physical objects in a subject or specific domain (Jonassen, 2004).

Conceptual knowledge refers to the collection of symbolic representations, space-time events, and physical things humans experience in life. Similar features shared by concepts and the similar relationships shared between concepts are used to describe classes of symbolic representations, space-time events, and physical things (Jonassen, 2004; Murphy, 2004).

Topology is a mathematical concept that defines a set of points, along with a set of shapes described by the points, and includes a definition of the relations between the shapes in a two-dimensional plane (Egenhofer, 1991; Mendelson, 1962).

Binary relations are a categorization of the eight possible topological relationships that can exist between two shapes in a two-dimensional plane (Egenhofer 1991, 1994).

Summary

This chapter presented a description of the origins and background that motivated my desire to conduct this case study. Chapter Two reviews the research addressing the use of diagrams as an elicitation technique for engaging the student's prior knowledge in a classroom setting. The review of the literature also includes a discussion of dissertations that address diagrams and student prior knowledge. Chapter Two also provides a discussion of constructivism as the conceptual framework that grounded this study within the historical context of learning theories.

Chapter Three describes the elicitation technique, materials, and the participants from each of the four different classroom settings. The subject domains represented in the case study included college teaching, project management, and operations management. The chapter includes examples of the student-generated diagram artifacts. Chapter Four provides an analysis of the elicitation exercise and of my observations working with the students and the instructors.

The study concludes with a discussion in Chapter Five of a summary of the observations, findings, and insights resulting from the experience of facilitating the diagram exercises, eliciting the abstract diagrams from the students, and performing the pattern analysis of the diagram topology across the four classroom settings. The study recommends avenues for further research and study.

CHAPTER TWO – LITERATURE REVIEW

This chapter describes the background, theoretical framework, and literature related to diagrams and prior knowledge. My preparation for developing the diagramming technique included a literature search in preparation for a class project (Klunk, 2009). That initial search did not produce any results specifically focused on diagramming prior knowledge. I was fortunate during my research for this case study that Purchase (2014) published a summary of diagram research based on conference proceedings covering the period 2000 through 2012. She established the Larkin and Simon (1987) article as marking the beginning of the diagram research field. Her summary of diagram research covered 177 papers and 135 posters. Her research served as an important tool for me in placing my work within the historical timeline of the diagram research literature.

I consider Larkin and Simon (1987) the foundational document in the field. The authors made a clear distinction between abstract diagrams and concrete diagrams. Abstract diagrams played a prominent role in my research. This chapter reviews the literature relevant to the use of abstract diagrams as a technique for eliciting prior knowledge and concludes with a summary of how my study contributes to the body of diagram research.

Background

During my research in 2009, I could not find literature related to the use of abstract diagrams in the classroom. I was familiar with the research by Herbert Simon related to problem solving (Newell & Simon, 1972) based on my studies during the period 1982-1985, while a graduate student at the University of Southern California. His later collaboration focused on diagrams (Larkin & Simon, 1987) and surfaced as an important resource for me while preparing for the class project in 2009. Larkin and Simon did not perform any experiments or involve any participants as part of their 1987 study. To the contrary, they begin the paper with a definition of an abstract diagram. Diagrams are a node-link data structure that exhibits advantages over text when used to communicate information to the viewer. They used several problem statements in physics, geometry, and economics to illustrate how a diagrammatic representation allows for more efficient search, recognition, and inferences by the human mind. They pointed out that the mind processes spatial and geometric topology with greater ease and efficiency when compared with the processing of textual information.

The survey by Purchase (2014) covered diagram research beginning with the work of Larkin and Simon in 1987. Her introduction included a definition for the term *diagram,* which she defined as “a composite set of marks (visual elements) on a two-dimensional plane that, when taken together, represent a concept or object in the mind of the viewer” (Purchase, 2014, p. 59). Her definition was similar to that of Larkin and Simon. I used this definition in my study.

Purchase organized her research by making a distinction between concrete diagrams and abstract diagrams. Concrete diagrams have a direct visual relationship to the object they depict. Abstract diagram have an indirect relationship to the object or concept. My study focused on abstract diagrams. Research by Purchase (2014) noted that abstract diagrams appeared rarely in the literature. She identified the Larkin and Simon (1987) work as foundational, but revealed that diagram use in the classroom was mentioned in only three works covered in her survey (DeLeeuw & Hegarty, 2008; Epstein & Keibel, 2002; Manalo & Uesaka, 2012). These researchers addressed diagrams in the form of spatial mental models as problem representations, how diagrams influenced language ability and imagination, and the role of diagrams in human problem solving. Her observations confirmed my own research experience where I found very little literature regarding the use of abstract diagrams in the research literature. The majority of diagram research was based on diagrams that included notations and embellishments in the form of lines, arrows, dots, and labels. These make diagrams more concrete.

In this case study, I was particularly interested in the advantages that minimalist, abstract diagrams afforded the viewer, in a way that improved the recognition of differences between indices. Larkin and Simon (1987) illustrated how the indexing system of nodes and links in a diagram preserve the topological and geometric relations of the indices. They did not provide a method for classifying these differences found in the indexing system.

This problem was solved by Egenhofer (1991). He described the differences between two node-link indices using the concept of binary relations. These relations preserved the topological and geometric features between the two shapes. I used geometric shapes for my project in 2009. I did not have a way to explain the differences in the diagrams in a qualitative way for that project. It was during the research for this study that I discovered the work by Egenhofer (1991, 1994) related to topology. His work provided the missing link back to the study by Larkin and Simon

(1987). The binary relations provided a way for me to understand and describe the differences in the shapes when comparing the diagrams created by the students.

The problem posed in this case study was that of the university professor who wants to engage the students and make their prior knowledge of concepts in a domain of study easy to recognize and easy to infer differences. Abstract diagrams make it possible to search for and recognize differences with less mental effort than with the use of textual information. Representing misconceptions of prior knowledge using abstract diagrams in this way is a novel approach. This technique for creating a visual foundation of conceptual knowledge supports the recommendations cited by the National Research Council (Bransford, 2000). These differences can be expressed using the language of binary relations (Egenhofer, 1991). These differences in conceptual understanding can then be characterized in qualitative, topological terms: disjoint, contains, inside, equal, meets, covers, covered by, and overlap. These qualitative features of a diagram topology are discussed later in this chapter.

Literature Survey Rubric

The goal of my literature review was to find research related to diagramming, prior knowledge, and university classroom settings. The majority of the research reviewed by Purchase (2014) concerned concrete diagrams, although several studies did relate to abstract diagrams. I created a question rubric to help identify research that met the goal of my review. The literature survey rubric assisted me in identifying applicable studies. Given the differences in how researchers define diagrams, prior knowledge, and student-generated diagrams, the rubric functioned as a tool for organizing the studies in a systematic way. The questions are described below. A short description following each question provides my logic in applying the question to the literature under review.

1. Did the article reference the Larkin and Simon article from 1987? In my detailed review of Purchase (2014), Egenhofer (1991), and Larkin & Simon (1987), it appeared to me that Larkin & Simon's presence in the references of an article was a strong indicator of the article's point of view. After reviewing several hundred abstracts that contained *diagram* in the keyword list, many did not contain the citation for the Larkin and Simon article. These data were very useful in separating research

into abstract diagram research and concrete diagram research. As Purchase (2014) found, very little research was available that addressed the use of abstract diagrams.

2. Did the article describe abstract diagrams using a definition similar to that provided by Larkin and Simon (1987) or Purchase (2014)? Abstract diagrams contained node-link, point-line geometry. Determining how the researcher defined a diagram was useful in the assessment of the study and how it could be applied to my case study. None of the articles contained diagrams that met the strict definition of node-link data structures.
3. Did the diagram described in the article reference the Egenhofer (1991) topology of binary relations? Egenhofer is considered a seminal thinker in the geographic information systems (GIS) community and was the creator of the topology used to describe the eight binary relations. If the article did not reference his work or that of another researcher mentioning diagram topology, this lack of reference was noted.
4. Was the diagram generated by the student? The article by Larkin and Simon (1987) stated that their research showed how mental images and mental processes in the brain could be well represented by external symbolic diagrams. Studies that did not include student-generated diagrams were also annotated as such. I was specifically interested in the diagrams generated by students. Diagrams created by others and used to make inferences about what a student might be thinking is a much more difficult psychological research effort. Techniques for conducting such mind-reading experiments are still considered experimental (Goldman, 2006).
5. Was the diagram intended to represent the student's prior knowledge? Purchase (2014) identified diagram research that included the use of student-generated diagrams. Upon closer inspection, these diagrams were concrete and contained the addition of notations and embellishments. The focus of my case study was the representation of prior knowledge using abstract diagrams. I made an annotation of the research that included student-generated diagrams and then further categorized the type of diagram as either abstract or concrete.

The rubric helped me define the nature of the gap in the literature. I noticed a general pattern that emerged through my use of the question rubric. The first group of articles did not cite or reference Larkin and Simon (1987). The second group of articles did cite Larkin and Simon

(1987) but did not cite Egenhofer (1991). The third group of articles included student-generated diagrams, but did not define diagrams in a way that qualified them as being abstract.

Prior knowledge was the other concept used in the question rubric. Research about prior knowledge appeared predominantly in the fields of educational psychology and the learning sciences (Amadieu, van Gog, Paas, Tricot, & Mariné, 2009; Cook, Wiebe, & Carter, 2008; Dochy et al., 1999; Meyer, 2004; Novick & Catley, 2014; B. Rittle-Johnson, Star, & Durkin, 2009; Williams & Lombrozo, 2013). I could not locate research about prior knowledge that also cited the works by Larkin and Simon (1987), Egenhofer (1991), or Purchase (2014).

There were studies that made reference to *elicitation* techniques. These studies characterized elicitation as a technique for understanding and documenting the knowledge of experts (Carrizo, Dieste, & Juristo, 2014; Dieste & Juristo, 2011; Gavrilova & Andreeva, 2012; Ley, Kump, & Albert, 2010), but did not include eliciting abstract diagrams. Three articles did surface related to graphic elicitation, but not eliciting abstract diagrams (Copeland & Agosto, 2012; Crilly, Blackwell, & Clarkson, 2006; Umoquit et al., 2013). The example of using the rubric to evaluate research that contained data related to elicitation was just one scenario in which the questions helped identify relevant research.

Conceptual Framework

The rubric was useful in filtering the research from the bottom up. The conceptual framework helped place the case study within the context from the top down of constructivism (Fosnot, 1996). Constructivist theory evolved from the writings and research of Dewey (1916), Piaget (1954), and Vygotsky (1978). Dewey viewed education as a practical experience, one that led to the construction of knowledge and skills by the student, for application to problem solving in daily life. His pragmatic philosophy was the foundation upon which Piaget and Vygotsky developed their psychologically-oriented theories of constructivism.

Piaget’s early work embraced the structure and role of wholeness, transformation, and self-regulation in psychological development (Piaget, 1970). This was followed by his later work which detailed his views on the role of cognition in human development (Piaget & Brown, 1985). He viewed thinking as an internal cognitive response to changes in the external environment. Cognition was an attempt to maintain a physical and psychological equilibrium in reaction to human experiences in the real world. Piaget further refined his characterization of equilibrium by referring to them as a process of assimilation and accommodation. This led Piaget to formulate his theory of equilibrium based on two postulates: “Every assimilatory scheme tends to incorporate external elements that are compatible with it…” and “Every assimilatory scheme has to be accommodated to the elements it assimilates…” (Piaget, 1985, p.6). This reminded me of the balance that a professor might seek in the classroom to assimilate and understand the prior knowledge of the students in a way that is equal to the objective.

In contrast to Piaget’s development theory, Vygotsky’s theory of learning and development positioned the student’s response to change as a socially mediated experience (Vygotsky, 1978). Vygotsky viewed learning and development as the outcome of shared social activities that are internalized by the student (John-Steiner & Mahn, 1996). Vygotsky conceived of the zone of proximal development as “the distance between the actual development level as determined by independent problem solving, and the level of potential development as determined with problem solving exercises, under adult guidance or in collaboration with more capable peers” (Vygotsky, 1978, p. 86). During my experience using the diagram elicitation technique, it occurred to me that the student diagrams represented a “zone of proximal conceptualization,” where the students use diagrams to explore their own knowledge of concepts as they anticipate the addition of new information. This concept is also present in the theory of conceptual spaces (Gardenfors, 2000, 2014).

The learning theory of Ausubel (1968) extended the constructivist philosophies of Dewey, Piaget, and Vygotsky in the form of his development of the advance organizer, a well-established technique for organizing the student’s prior knowledge in advance of new learning (Ausubel, 1960). The diagram technique described in this dissertation could be interpreted as a type of advance organizer, one that is manifested in the form of student-generated diagrams.

The advance organizer was followed by researchers who were influenced by the arrival of computers. These researchers developed constructivist techniques under topics such as knowledge management (L. Anderson & Krathwohl, 2001), knowledge ontology (Sowa, 1984), and knowledge taxonomy (L. Anderson & Krathwohl, 2001; Duffy & Jonassen, 1993). These techniques made it clear that conceptual knowledge was the most abstract form of knowledge when compared with declarative and procedural knowledge (Foshay, Silber, & Stelnicki, 2003).This insight from constructivist learning theory reinforced the choice of questions used in the diagram technique itself. I developed the elicitation questions to prompt the students to think conceptually when creating diagrams.

The differences of opinion regarding the role of constructivist theory in the classroom are documented in the literature (Kirschner, Sweller, & Clark, 2006; Tobias, 2010). I align myself with those in the research field who believe that graphic tools used by students in the classroom are constructivist by design (Barone & Cheng, 2005; Cheng, 2002, 2011; Cook, Carter, & Wiebe, 2008; Garcia & Pacheco, 2013; Kolloffel, Eysink, & de Jong, 2010, 2011; Rau, Michaelis, & Fay, 2015). I now turn to a detailed investigation of prior knowledge to better position the importance of using abstract diagrams to elicit the conceptual understanding of students.

Prior Knowledge

The rubric was also used to filter research from the bottom up that addressed prior knowledge. Ausubel (1968) is the best known advocate for engaging the student's prior knowledge in a way that supports the construction of new learning. More recent works advocated for engaging the student's prior knowledge as important part of building a foundation for new learning (Amadieu et al., 2009; Ambrose et al., 2010; S. Chen & Huang, 2013; Khosrowjerdi & Iranshahi, 2011; Rokers, 2007; Wetzels, Kester, & van Merriënboer, 2011; Williams & Lombrozo, 2013). Much of the prior knowledge research happens in domain-specific settings (S. Chen & Huang, 2013; Cordova, Sinatra, Jones, Taasoobshirazi, & Lombardi, 2014; Novick & Catley, 2014; Williams & Lombrozo, 2013). These articles follow a line of inquiry illustrated in the research by Gick and Holyoak (1980). They described how students transferred the prior knowledge of solving one problem to the task of solving a subsequent problem. Students were provided a hint by the researcher to re-read a story about how a similar problem was solved. This technique helped to activate memory of previous problem solving techniques.

Prior knowledge operates in settings outside the classroom as well. For example, research has shown how the prior knowledge of soccer matches and players led to a higher recall of soccer scores in one group than the recall of scores by those in another group with less soccer match viewing experience (P. Morris, Gruneberg, Sykes, & Merrick, 1981). I used the three different types of prior knowledge (declarative, procedural, and conceptual) to help the reader locate my study within the larger body of educational research literature. This distinction between these types is important. Framing conceptualizations by students within a domain of study provides insight into the general applicability of the diagram technique across subject areas and classroom settings.

Declarative Knowledge

The educational research literature categorized knowledge as being declarative, procedural, or conceptual in nature. The literature does not explicitly make distinctions between past knowledge, current knowledge, and future knowledge. The characterization of knowledge as being "prior" is discussed in greater detail later in this chapter. In this dissertation, prior knowledge is positioned as knowledge that is constructed by the student (Jonassen et al., 1993). The construction of *declarative* knowledge is characterized by facts, figures, events, and objects (Bolc & Carbonell, 1987). Declarative knowledge can be represented through spoken, visual, or written forms of communication (Deacon, 1998; Pinker, 1997). It can also be exhibited through the knowledge of how to do something, and communicated through action (Pouw, van Gog, & Paas, 2014), or through interactions with physical objects in the real world, such as navigating a ship or flying an airplane (Hutchins, 1995). This type of knowledge is thought to be stored in long-term memory in the form of mental schemas. These schemas or scripts enable the learner to know the "what" of a subject or domain (Bartlett, 1967; McVee, Dunsmore, & Gavelek, 2005; Schank & Abelson, 1977; Tversky, 2001).

Procedural Knowledge

The second type of knowledge described in the literature was *procedural* in nature and is the knowledge a student constructs to show they know "how" something works (Branch, 2009; Foshay et al., 2003). Procedural knowledge is knowing about the sequence of steps required to solve problems (Bethany Rittle-Johnson & Alibali, 1999). The goal of improving procedural knowledge is often based on the study of expert knowledge (J. Anderson, 1996; Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Farr, 1988; Ericsson, 2006; Farrington-Darby & Wilson, 2006; R. Hoffman, Shadbolt, Burton, & Klein, 1995; R Hoffman, Ward, & Feltovich, 2013; Larkin et al., 1980). The orientation of the research on procedural knowledge is very often domain-specific, and designed to cover specific skills and abilities (Canobi & Bethune, 2008; B. Rittle-

Johnson et al., 2009; Schneider, Rittle-Johnson, & Star, 2011). The majority of the diagram research reviewed by Purchase (2014) is focused around the study of how diagrams can be used to improve business processes (Laguna & Marklund, 2005).

Conceptual Knowledge

The third type of knowledge described in the literature was referred to as structural knowledge (Jonassen et al., 1993). Over time the educational psychology field came to see structure in all types of knowledge (O'Donnell, Dansereau, & Hall, 2002). The term *conceptual* knowledge better represented the students understanding of concepts and the relationships between concepts (Barsalou, Simmons, Barbey, & Wilson, 2003; Gardenfors, 2000; Sowa, 1984). Conceptual knowledge functions as a higher level construct that includes links to declarative knowledge and procedural knowledge (Thagard, 1992).

This dissertation is focused on the elicitation of the student's conceptual knowledge using a domain-general diagramming technique. The research addresses the use of diagrams in relationship to these three types of knowledge (declarative, procedural, and conceptual). Purchase (2014) identified abstract diagrams, student diagrams, and conceptual knowledge as one of the areas in which there was little representation in the research. Research related to diagrams is reviewed in the next section.

Diagrams

I used the question rubric to locate the relevant research that was directed at abstract diagram use in the classroom and grounded in the works by Larkin and Simon (1987), Egenhofer (1991), and Purchase (2014). While the literature reported various taxonomies for organizing diagram research based on the researcher's personal preferences, I chose to link abstract diagrams to a qualitative topology, and then follow the different threads of diagram research reported by Purchase to compare and contrast the research to my study goals. Examples of the variations that surfaced in the literature regarding diagram taxonomies, diagram standards, diagram terminology, diagram research frameworks, and diagram grammars are discussed below.

Research Taxonomies

Research taxonomies varied in the research according to Purchase (2014). She organized her review into nine topics: notations, translation between external representations of diagrams and semantics, the nature of diagrams, cognitive models of diagram comprehension, the study of diagram comprehension, internal diagram manipulations, tools that support diagram use, graphical literacy, and miscellaneous research. This taxonomy led to the discovery of other works that published various diagram taxonomies and were collected in a study by Blackwell and Engelhardt (2002). Their report had a diagram topology that included vocabulary, tokens, abstraction, structure, mode of correspondence, represented information, task and interaction, cognitive processes, and social context. The highlight of her work and review of these studies was in her categorization of diagram types being either abstract or concrete. She only found three articles or posters which covered abstract diagram use out of the 312 she reviewed (Purchase & Samra, 2008; Ware, Gilman, & Bobrow, 2008; Yoon, Narayanan, Lee, & Kwon, 2006). None of these three studies included concepts related to student-generated diagrams, prior knowledge, diagram topology, or elicitation techniques.

Standards and Terminology

Purchase (2014) pointed out that diagram research standards and terminology vary. This was also confirmed by research originating in the health care domain (Umoquit et al., 2011). The variation in diagram research taxonomies extended to diagram use in grounded theory (Buckley & Waring, 2013), diagrams used to augment research in cognitive architecture (Chandrasekaran, Banerjee, Kurup, & Lele, 2011), diagram use in visual language theory (Cheng, 2014; Flower, Stapleton, & Rodgers, 2014; Gottfried, 2014, 2015), diagrams in a descriptive role in knot theory (De Toffoli & Giardino, 2014), diagrams used in political science research (Mahoney & Vanderpoel, 2015), diagrams used in problem solving research (Mahoney & Vanderpoel, 2015), and diagram use in understanding tree thinking skills of college students (Phillips, Novick, Catley, & Funk, 2012). This may help explain the gap in the literature regarding abstract diagram research.

Research Frameworks

A study by Cox (1999) described how graphics generated by students in the course of solving problems took many forms, and included more than just diagrams (tables, charts, lists, sketches, matrices). Diagram research extended across many disciplines (Adesope & Nesbit, 2013; Ainsworth & Loizou, 2003; Cromley, Bergey, et al., 2013; Kalyuga, 2008; Maries & Singh, 2012; Moreno, Ozogul, & Reisslein, 2011; Uesaka, Manalo, & Ichikawa, 2007). There did not appear to be a general diagram research framework that was common and in use across research disciplines. This led to the insight that a more fundamental concept, that of diagramming as a type of visual language, and the geometric shapes as grammars, might inform the role and use of diagrams in the classroom (Brna, Cox, & Good, 2001; J. Burton et al., 2014; Hyerle, 1996; Marriott & Meyer, 1998; Tversky, 2011; Wheeldon & Ahlberg, 2012). The research linked diagrams to research in shapes.

Shape Grammars

Abstract diagrams surfaced in the field of architecture, but are referred to as shape grammars, and considered a form of a visual language (Marriott & Meyer, 1998). This research is a sub-field of study within computer science and cognitive science. Within this area of study, three approaches are used to specify a visual language: grammatical, logical, and algebraic. Shape grammars were first specified in works by Gips (1975) and Stiny (1975). A shape grammar is a specification using shapes placed in a diagram. The diagram has a vocabulary (shapes), a set of rules (topology), and a technique for producing new sentences (elicitation questions and constraints). The study of shape grammars is confined to the fields of environmental planning, computer-aided design, and architectural design (Benros, Duarte, & Hanna, 2012; Knight, 1999; Yue & Krishnamurti, 2013). This narrow use of abstract diagram grammars may be another reason why a gap exists in the diagram research literature. Visual languages are a new, but still unknown discipline and not represented in the literature reviewed by Purchase (2014). To investigate the research since 2012, the next section reviews recent dissertations that addressed diagrams, prior knowledge, student-generated diagrams, and elicitation techniques.

Dissertations

A general search of dissertation databases led to an initial collection of dissertations that contained various combinations of keywords that included diagrams, prior knowledge, elicitation, and students. A search using constructivism was also performed to locate literature that might exist in the educational research domain. This first step resulted in a set of a 136 dissertations. Much like the experience encountered by Purchase (2104), the further inspection of the abstracts revealed ambiguities in how the terms were used to code the studies by the dissertation authors.

Thirteen dissertations qualified as meeting some part of the question rubric. I was looking for dissertations in the literature that discussed the use of diagrams created by students. I was looking for data that reflected similar findings by Larkin and Simon (1987) that showed how abstract diagrams improved search, recognition, and inference. I was also looking for data that indicated the researchers knew of or included references to the work by Egenhofer (1991). These dissertations are discussed below and organized in the order of the rubric questions. The discussion of the dissertation follows the question.

1. Did the dissertation reference the Larkin and Simon article from 1987? The dissertation by Karrass (2012) was the only study that referenced the Larkin and Simon article. He used arrows, lines, and labels to embellish the diagrams in the form of sketches for geometric proofs. The labeling made the diagrams more concrete than abstract. The study also used computer mediated technology to generate the proofs and did not represent an external representation of the internal processes of the students thinking. The technology was also domain specific and useful in the mathematics domain.

2. Did the article describe diagrams using a definition similar to that provided by Purchase (2014) and qualify as abstract diagrams? The dissertations in the next group were selected because they were indexed under the keyword diagram. Upon closer review, the diagram techniques used in the studies were actually techniques better described as drawing (concrete pictures), sketching (storyboards), and creating iconic representations (concrete objects found in biology and ecology). These works did not cite the Larkin and Simon article from 1987 and did not define a diagram as a minimalist, abstract, type consisting of node-link geometric shapes. There was no discussion of an underlying typology of student conceptualizations of prior knowledge.

3. Did the diagram described in the article reference the Egenhofer (1991) study? The diagrams described in the thirteen dissertations all used enhancements,

embellishments, and annotations, which rendered the diagrams very concrete in their appearance and use. This concrete type of diagram reduced the recognition of any underlying binary relations that might have been present in the diagrams. None of the studies included digital copies of the diagrams other than an exemplar. This made it impossible to assess if differences were present in the diagram topology.

4. Was the diagram generated by the student? Nine of the dissertations were situated in a university classroom and included a mix of undergraduate students, graduate students, and student teachers attending pre-service training (Adesope, 2010; Asmuth, 2009; Bussey, 2013; Karrass, 2012; Kline, 2012; Madsen, 2013; Pastore, 2009; Rosengrant, 2007; Yestness, 2012). Again, in the above studies, the diagrams were composed of extensive forms of enhancements, embellishments, and annotations, all with the intent of representing procedural and declarative knowledge. Diagrams were not used to represent conceptual knowledge. Diagrams were generated by students in only five instances (Bussey, 2013; Landin, 2011; Pillsbury, 2008; Rosengrant, 2007; Yestness, 2012). The students in two cases were middle school students (Pillsbury, 2008). The diagrams that were created in all cases were of a concrete nature and fell outside the definition of a node-link, abstract diagram as defined by Purchase (2014).

5. Was the diagram a representation of the student's prior knowledge? Seven of the dissertations described an exercise in which the students were asked to illustrate their knowledge. The elicitation questions in all cases asked about declarative or procedural knowledge, using techniques of sketching, drawing pictures, or diagrams that included enhancements, embellishments, and annotations (Bussey, 2013; Jessee, 2012; Karrass, 2012; Landin, 2011; Li, 2013; Pastore, 2009; Pillsbury, 2008). None of the dissertations used questions to prompt the student for their prior knowledge of concepts or conceptual understanding. When students were asked to create diagrams, the techniques were specific to the domain under study. For example, using formula notation in mathematics was not transferrable to diagrams in the domain of biology.

In summary, the manner in which these dissertations described the use of diagrams, how diagrams were defined, how diagram use was implemented in the classroom, and how diagrams were used as an instructional intervention, varied widely. The studies conducted outside the university setting (high school and middle school) are noted under the author names. None of the dissertations used abstract diagrams. Table 2.1 contains the summary of the research.

Table 2.1

Dissertations Summary According to the Question Rubric

Study Author	Cite L& S	Cited Purchase	Cited Egenhofer	Student Diagram	Elicit Prior Knowledge	Concrete Diagram Types
Adesope 2010	No	No	No	No	No	Concept maps of the human nervous system
Kline 2012	No	No	No	No	No	Physics diagrams of air pumps, carburetors, toilet arrows
Asmuth 2009	No	No	No	No	No	Geometric diagrams of hyperbolic lines, closed figures
Madsen 2013	No	No	No	No	No	Physics diagrams with lines, labels, text, numbers, icons, symbols
Rosengrant 2007	No	No	No	Yes	No	Free body diagram
Yestness 2012	No	No	No	Yes	No	Algebra proofs
Karrass 2012	Yes	No	No	No	Yes	Axioms, sketches, parallelograms
Li 2013	No	No	No	No	Yes	Engineering free body diagrams
Jessee – 2012 *High School	No	No	No	No	Yes	Charts, graphs in civics and economics
Pastore 2009	No	No	No	No	Yes	Drawing with text of human heart
Bussey 2013	No	No	No	Yes	Yes	Protein translation
Landin – 2011 *Middle School	No	No	No	Yes	Yes	Biology tree taxonomy
Pillsbury – 2008 *Middle School	No	No	No	Yes	Yes	Ecology tree taxonomy

*Studies involved university students except where noted.

Three studies were the most representative in approximating an understanding of student-generated diagrams as a tool for knowledge discovery, but were aligned to very specific domains. Research by Bussey (2013) was situated in a university biochemistry class setting and showed how the appropriate level of diagrammatic abstraction was important to how well the student acquired the new learning, but the diagrams were concrete in nature. Research by Landin (2011) supported the idea that drawing about biology concepts improved learning in the laboratory, but these drawings were also concrete in nature. Research involving middle school students by Pillsbury (2008) used pictorial drawings in place of diagrams to assist in the scaffolding of student learning in a semester long project in ecology. The techniques were not generally applicable across subject areas.

Summary

The literature review expanded on the initial review first conducted for the class project in 2009. My experience of not finding research related to diagramming prior knowledge led to the literature search described in this chapter. The story of diagram research is told along the review by Purchase (2014), wherein she established the work by Larkin and Simon (1987) as the foundational paper in the diagram research field. They mentioned topology in their paper and this reference led to the discovery of topology relations described by Egenhofer (1991). His work provided the framework for understanding the qualitative nature of binary relations in abstract diagrams. Chapter Three describes the diagram technique, the classroom setting, and the participants. The analysis of the data is provided in Chapter Four. I close the case study in Chapter Five with discussion and interpretation of my findings and recommendations for future research.

CHAPTER THREE - METHOD

This chapter describes the diagram technique, the participants, the data collection, the approach to data analysis, and the references that contributed to the organization of this method section of the case study. The diagram elicitation technique was used to collect data from the students in the form of abstract diagrams. The elicitation questions were based on a report by the National Research Council (Bransford, 2000). The report summary noted three observations common to student behavior when they enter the classroom at the beginning of a new semester. Students enter the classroom with prior knowledge, a unique way of storing information in long-term memory, and personal strategies for monitoring their own learning. My personal experience as a graduate student and adjunct professor validated the challenges that students and instructors go through when meeting for the first class. This chapter describes a technique designed to help facilitate this introduction to new material at the beginning of the semester using a technique for diagramming prior knowledge.

Background of the Elicitation Technique

The elicitation technique presented in this chapter is based on research by Larkin and Simon (1987) who described advantages of diagrams over text when communicating information. They argue that differences in diagrams are easier to recognize. The use of student-generated, abstract diagrams appeared to be a gap in the literature based on the discussion in Chapter Two. I designed this elicitation technique for general use by university instructors as part of this case study. Students are provided crayons and three blank sheets of paper. Three questions are used to elicit responses in the form of diagrams. The students have five minutes to draw an answer to each question in the form of an abstract diagram. The diagrams can only contain triangles, squares, and circles. They cannot use letters, numbers, labels, symbols, icons, special characters, or other marks.

The elicitation technique was also based on a prototype of the technique first developed for a graduate school project in 2009 (Klunk, 2009). The version of the technique described in this study was changed to minimize the cost of materials by using blank paper and crayons. I also adapted the questions to fit a domain specific course. My experience conducting similar facilitations with small teams in industry and government settings are often followed by week-long working groups, during which we develop conceptual models and problem-specific vocabularies. The time limitations placed on the schedules in the university classroom environment, prevented me from conducting these type of activities during this case study

Constructivist Orientation to Diagram Elicitation

This case study adopted a constructivist view of the processes related to students creating diagrams of prior conceptual knowledge that was discussed in the context of other research in Chapter Two. The elicitation technique is general in nature and designed to be adapted to many domains and subject areas. The research questions were developed to explore the nature of diagramming prior knowledge in the university classroom setting. The questions are provided below.

- How can abstract diagrams constrained by domain-general, geometric shapes be operationalized in a diagram elicitation technique, and thereby make prior knowledge of the students accessible visually within the context of a domain-specific classroom setting?
- How can the diagrams offer learners the opportunity to collaborate and share diagrams that could lead to the creation of shared prior knowledge?
- To what extent does the instructor perceive the diagram technique to be useful as a tool for eliciting prior knowledge at the individual level and at the group level?

Organization of the Data

The research data was organized according to two principles. First, the interactive model of research design (Maxwell, 2013) was chosen to provide a structure that enabled a many-to-many set of relationships between the individual diagrams, the diagrams within a class, and the diagrams as a singular collection of case study data. Second, the case study adopted the *unit-of-analysis* concept to structure the comparison of similarities and differences between the diagrams (Yin, 2009). The unit-of-analysis approach defines a boundary around each set of data created by the student in the form of a diagram. The student diagram represented a collection of prior knowledge concepts rendered in the form of geometric shapes on the blank paper. This approach to guiding the students in producing abstract diagrams had the unintended outcome of making visible a hidden topology in each diagram.

Interactive Structure

The value of the interactive structure advocated by Maxwell derives from the framing of the diagrams as the central piece of data that establishes links between the study goals, theoretical framework, units of analysis, and the tests of validity. The structure also aligned with the organization of the data as representing a topology. The analysis addressed the hidden patterns found in the topology of the diagram shapes. At first glance, diagrams of this type appear to have nothing in common. The data analysis uses binary relations embedded in the topology to make the relations explicit. What might appear to be just a collection of student-generated diagrams of unlimited and random combinations are actually a visual representation of hidden patterns of conceptual relationships and prior knowledge rendered as diagrams.

Participants

The participants in this study included the students and the sponsoring instructors. I performed the tasks of facilitating the diagram elicitation technique. The instructors hosting the facilitation in their classrooms observed the creation of the diagrams by their students, but did not participate in the diagramming technique. Each class was comprised of students who agreed to create diagrams at the invitation of their instructor. Students were provided the opportunity to opt-out of the exercise at the beginning of the class, but none did so. Selection criteria, confidentiality, protection of the participant identity, and researcher biases are discussed in the following sections.

Students

The students were enrolled at four universities located in the eastern United States, two groups in graduate level classes, and two groups in undergraduate level classes. One university was located more than fifty miles from a major metropolitan area. The second location was a suburban campus located outside a major metropolitan area. The remaining two facilitations took place in urban campus locations. One institution was a privately chartered university and the others were state chartered public universities. The diagram technique did not require any specific classroom configuration, layout, or equipment. The classroom settings accommodated the diagram facilitation equally. I did not collect demographic data. There appears to be little existing research that could provide a basis for qualitative or quantitative correlations, or meanings that might be related to attempting to map shape styles and configurations to student gender, age, or ethnicity.

Student selection method. The students participating in the case study were invited to do so through an email communication originating from the sponsoring instructor. The instructor notified the students in advance of the facilitation exercise. The date and time were proposed in advance. Students were provided the opportunity to opt-out of the exercise in advance. On the day of the facilitation, prior to the commencement of the classroom session, the students were also provided the opportunity to opt out of the exercise. The instructors explained that there were no prerequisites required for participation in the exercise and that it was not part of any course assessment.

Student confidentiality and anonymity. The confidentiality of the students was maintained in several ways. First, the diagramming materials provided to the students consisted of blank paper and crayons. These materials did not contain any markings that would identify the student. Second, the diagrams contained a blank line at the top of the page. The students were asked to think of a random eight digit string containing letters and numbers. Each student was instructed to place the same alphanumeric string at the top of each of the three sheets of blank paper. This unique string served as an identity label for organizing the diagrams in sets without disclosing their personal identity. I also asked the students to place a classroom code at the top of the three pages to identify each classroom. The student diagrams were collected by a student volunteer at the completion of the exercise. The volunteer placed the diagrams in an envelope and returned the envelope to me at the conclusion of the facilitation event.

Instructors

I invited the instructors to participate in the case study based on a personal and professional relationship. They had expressed a shared interest in the use of diagrams in the classroom. I provided the instructors with the background, history, and artifacts representative of the diagrams and technique. The instructors were provided a copy of the Institutional Review Board application prior to their agreement to participate in the facilitation exercise.

Instructor confidentiality and anonymity. The confidentiality of the sponsoring instructors was protected by excluding the use of data related to classroom settings, instructional syllabus, or student enrollment. The instructors did not participate in the diagram elicitation exercise.

Participant Biases

I used a minimal set of instructions and basic shape rules to minimize bias that might be introduced by the instructors and students to the data collection technique. The abstract nature of the diagram does not guarantee that some diagrams may be a marginal effort on the part of the student when creating a conceptual diagram of their prior knowledge. The type of bias I have experienced in the past when using this technique in a work setting, takes the form of a participant choosing not to create diagrams. The other response I have observed that would qualify as a form of bias is the creation of highly primitive diagrams that violate the shape rules in which the allowed forms are triangles, squares, and circles. The instructors did not create diagrams. I did collect data from the instructors in the form of a set of questions. They reserved the right to opt out of responding to the questions. One instructor did respond to the questions.

To minimize my own bias as the researcher as I interacted with the student participants during the facilitation of the elicitation exercise in the following way. I provided the students with blank paper and crayons. I did not engage in any diagram instructional interventions other than reading the diagram instructions. The instructions I used are provided in the appendices.

Data Collection

The data collection technique described in this study was created based on a prototype that was created for a graduate school project in adult learning facilitation (Klunk, 2009). This section includes a description of the history and background of the prototype. Changes made to the prototype for use in the case study are noted in the following section.

Prototype

The idea of using a diagram technique in the class project and the case study grew out of my professional experience creating entity-relationship diagrams (E-R) in my role as a data architect. E-R diagrams are highly constrained diagrams that describe logical and physical models of computer information systems. The E-R diagrams serve the purpose of translating the business user’s conceptual requirements into the technical user’s conceptual designs. This diagramming experience in industry led me to the idea of using diagrams as a technique in the class project in 2009. The elicitation technique was later modified slightly to accommodate the facilitation in larger classroom settings.

Materials

The diagram prototype technique created for the adult learning class (Klunk, 2009) used large sheets of white poster paper, geometric shape foam pieces, and glue sticks. The materials used in the prototype were effective in engaging the students in knowledge construction activities. Using identical materials was not deemed manageable when used in a larger university classroom setting due to time and material constraints. This led to the decision to use paper and crayons in the university classroom facilitations.

Stimulus Questions

The format for the stimulus questions was based on statements made in the National Research Council report on learning in the classroom (Bransford, 2000). The report included three observations that related to student epistemology, long-term memory, and meta-cognition. These insights provided the basis for creating three stimulus questions for use in the elicitation technique. The format of the three questions is provided below.

How do you think _______ works?

How do you store information about ______ in long term memory?

How do you monitor your own learning about ______?

The question formats were constructed as templates for use by instructors in a subject domain. The questions function as fill-in-the-blank type of diagram elicitation stimulus questions. For example, the questions provided below illustrate how they appear when *how*-type questions are used in an elicitation exercise for a class in adult learning. For such an introductory course, it could be useful for the instructor to quickly assess how varied the student's conceptualizations of prior knowledge about the concept of adult learning that they bring with them to the classroom might be. Note that this technique could have been applied to virtually any domain of learning in any class on any topic—its application within a course on adult learning was purely opportunistic.

Some students may have a background in elementary education, some may be professional trainers working in a corporate setting, and others may be researchers for a not-for-profit social services outreach organization serving minority communities. Each student would likely have a unique perspective as to how adult learning operates in the real world. This scenario describes the setting that was the basis for the experimental prototype conducted in 2009 as part of the class project.

The sample questions are provided below as an illustration of how questions appear in this context.

How do you think *adult learning* works?

How do you store information about *adult learning* in long term memory?

How do you monitor your own learning about *adult learning*?

Diagram Elicitation Procedures

The steps facilitating the diagram elicitation technique are described below.

1. Explain to the students that they will be participating in an exercise that asks them to create diagrams using geometric shapes in response to three questions.
2. Explain to the students that the objective of the diagram exercise is to enable them to share their individual interpretations with others in the class of how they conceptualize their prior knowledge and experiences about concepts in a subject domain.
3. Explain to the students that they will have five minutes to complete each diagram in response to each of three questions.
4. The instructor has the option of asking the students to explain their diagrams to fellow students upon completion of the exercise.
5. Hand out the materials to the students. Each student is given three sheets of blank paper and several colored crayons they select from a box of crayons.
6. Once the students have received the materials, ask them to think of a random eight digit number. Ask them to write the number in the upper right hand corner of the three sheets of paper. Explain to them that this random number is used to reassemble the sheets of paper in the event that the diagrams become

separated. Repeat for the student's benefit how the number should not contain any personal identifying marks embedded in the string such as social security numbers, birth dates, or similar identity numbers. The instructor can also modify the instructions to change the number sequence to a sequence of random numbers and letters.

7. The next step in the process is to explain to the students that the diagrams can only contain triangles, squares, and circles. The diagrams should not contain any other markings. Letters, numbers, special symbols, lines, arrows, points, or another marks are not allowed as part of the diagram constructions. Explain to the students that they are free to create the diagrams using the geometric shapes in any configuration, composition, quantity, order, or layout.
8. Before proceeding with the timed portion of the facilitation ask the students if they have any questions.
9. State the questions one at a time. Allocate five minutes for each question. Remind the students to fill in the blank with the question topic. Announce to the students that they can begin to answer the first question. At the four minute mark, announce to the students that they have one minute left. Ask the students to complete the diagram for the first question at the five minute mark. Ask the students to turn the diagram face down. Repeat the timed portion as described above for the two remaining questions.
10. At the completion of the timed diagramming period, ask the students to pass the diagrams to the student volunteer assigned to collect the diagrams. Ask the volunteer to place the diagrams in an envelope and hand the envelope to the facilitator or instructor. This completes the steps involved in conducting the facilitation exercise.

Data Analysis

The data were collected in the form of student-generated, abstract diagrams. Researchers use many approaches when analyzing diagrams. The study of diagrams is predominantly *quantitative* in nature (Purchase, 2014). The approach taken in this study was based on the *qualitative* nature of a topology that is embedded in a diagram (Egenhofer, 1991). The qualitative attributes of a topology are characterized by the visual representation of the relationship between two shapes. These relations were used to identify how differences in the student diagrams can be distinguished. The shapes used in the diagram technique described in this study were constrained to the use of the geometric shapes of triangles, squares, and circles.

Analysis of Student Diagrams

The analysis of the student diagrams was conducted with several aims in mind. The first objective was to determine how the diagram technique could be made operational in different classroom settings. The second objective was to determine how the differences in the diagram representations (relations between shapes) could foster student sharing and collaboration when constructing conceptualizations of prior knowledge. The third objective was to solicit instructor feedback based on their experience of observing the facilitation exercise.

Unit of Analysis

The three objectives described above were used to compare and contrast the diagram artifacts collected from each of the four facilitation exercises. The analysis of the diagrams collected from each of the four units served as the basis for making observations regarding the generalization of the technique across subject domains. For example, the subject domain under study in one of the classroom settings was *college teaching*. The diagrams represented in Figure 3.1 depict the general diagram layout and aesthetics present in abstract diagrams generated using the technique described in this study.

The collection and storage of the abstract diagrams involved three steps. First, the physical diagrams were collected from the students. Second, the diagrams were then scanned and converted into a digital file format known as Portable Document Format (PDF). Third, the diagrams were organized in the storage media by creating a directory folder for each of the four classroom settings.

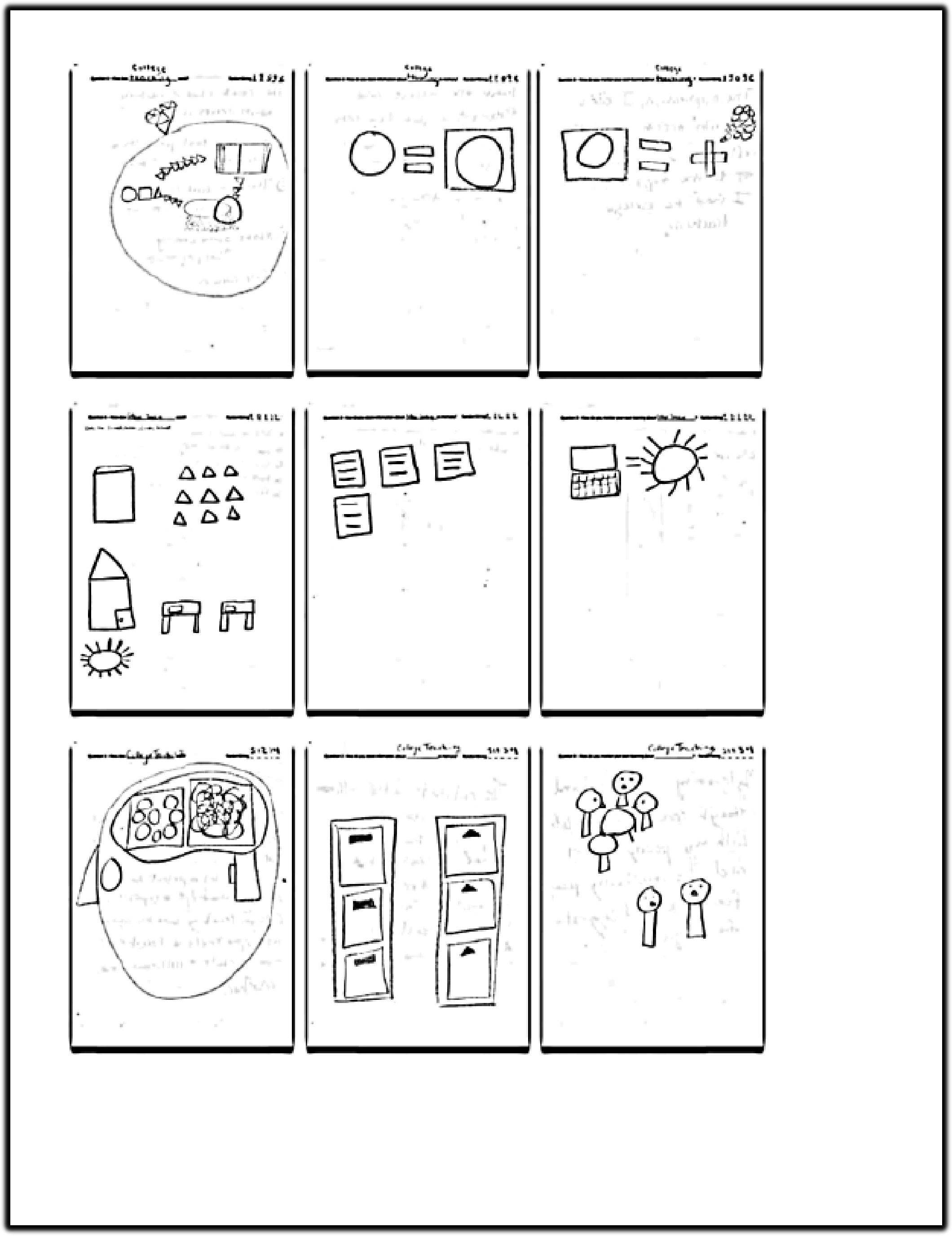


Figure 3.1. Diagrams by students taking class in subject domain of college teaching.

Stimulus questions. Three stimulus questions were used to elicit a response from the student. The use of the word “how” in the elicitation question had the effect of guiding the student to think about concepts in a way so they could produce a shape constrained to forms of triangles, squares, and circles. The question template was used in all four classroom settings.

Binary relations. The binary relations that existed between the shapes placed by the students in each diagram were used as evidence of the visual variation that is recognizable as differences in prior knowledge conceptualizations. The possible binary relations that can exist between two shapes are disjoint, meet, equal, inside, covered by, contain, cover, and overlap. These are based on concepts of topology (Egenhofer, 1991; Egenhofer & Golledge, 1998; Mendelson, 1962).

Validity

The traditional strategies for reporting validity include member checking, triangulation, viewer description, peer reviews, and external audits (Merriam, 1998, 2009). Data collection using diagrams benefits from the unique features of diagrams when used to communicate information (Larkin & Simon, 1987). The value of data collection in the form of diagrams is that observers can check their own perceptions in a direct way when the artifacts are visual (Bagnoli, 2009). The similarities and differences represented in the diagrams allowed triangulation through the relational lens of a topology (Mendelson, 1962). Students, instructors, and researchers have equal access and can cross-check peer reviews with self-reporting instruments.

The abstract diagrams generated by the students can be interpreted by the viewer in very personal ways. Each diagram is open to interpretation by viewers based on their own personal perception of visual features. Personal observations can be made by anyone who views the diagram artifacts. The research design in this case included descriptions of the setting, the diagram intervention techniques, the description of the diagram outcomes, and samples of the diagrammatic evidence to support validity checking (Burchett et al., 2011). The diagrammatic artifacts used student-generated, randomized identity strings to provide a visual marking that verified that the diagram belonged to a specific classroom unit.

Reliability

The case study addressed the test of reliability in several important ways. The technique was first tested for reliability after the prototype exercise in 2009. The results were compared to similar behaviors observed when creating E-R diagrams in the work setting. Given a clear set of constraints as part of the diagram rules, the resulting artifacts could be expected to share similar features. In this case, the similarity was in their predictable differences. The second test occurred when the diagram technique produced similar outcomes and findings in all four classroom settings. The use of the same materials, instructions, and diagramming rules led to similar outcomes. All the student-generated diagrams were different. The design of the diagram elicitation technique is guided by the goal of minimizing errors and reducing researcher biases.

Analysis of Instructor Interviews

The original strategy was to conduct instructor interviews after the completion of the exercises. The instructors did not participate in the diagram exercise, but did observe the students creating the diagrams. I developed a set of questions and provided these to the instructors. The questions are provided in the appendix. One of the two instructors responded and these comments are discussed in the next chapter.

Summary

The diagram elicitation technique described in this chapter originated as part of a class project for a graduate school course in 2009. That experience led to the modification of the technique in a way to support instructor use in specific classroom settings. This chapter described the participants, the materials used in the technique, and the steps involved when facilitating the technique in a university classroom setting. The chapter also described the qualitative nature of topological relations that exist between shapes. Questions were provided to the instructors and a copy is included in the appendices.

Each student was asked to generate three diagrams in response to questions related to student conceptualizations about prior knowledge, how they store those concepts in memory, and how they monitor their own learning about change related to those concepts. The chapter included an example of one set of diagrams that was collected in one of the classroom exercises. The literature review indicated that the use of abstract diagrams is not a focus of diagram research. The detailed discussion of data related to this technique and the research questions is provided in the next chapter.

CHAPTER FOUR – ANALYSIS

The qualitative data analyzed in this chapter consists of my observations made, diagrams produced by the students, and responses to a list of questions provided to the instructors. The analysis of the data was organized around the three research questions. The first question was concerned with operationalizing a diagram technique. The second question focused on student collaboration. The third question addressed feedback from the instructors regarding their experiences.

The analysis of the elicitation technique itself was based on research by Larkin and Simon (1987). They described why differences in diagrams were easier to recognize when compared with text. The analysis related to student collaboration was based on the binary relations described by Egenhofer (1991). The analysis of the instructor experiences and feedback with the diagram technique was framed within the larger context of diagram use in the university classroom setting.

Research Question One

The first research question contained two parts. Part one focused on how to make the technique operational. How can abstract diagrams constrained by domain-general, geometric shapes be operationalized in a diagram elicitation technique?

In pursuit of this sub-question, I facilitated the diagram technique described in Chapter Three. The objective was to facilitate the technique and observe the students constructing the diagrams in four separate classroom settings described in Table 4.1.

Table 4.1

Classroom Setting and School Location

Class Subject	School Location	Student Status	Class Size	Instructor ID
College Teaching	Rural State University > 20,000 Students	Full-Time, Graduate Students	12	A
Program Operations Management	Urban Private University < 5,000 Students	Full-Time, Undergraduate Students	28	B
Project Management	Suburban State University > 10,000 Students	Part-Time, Graduate Students	18	B
Project Management	Suburban State University > 10,000 Students	Part-Time & Full-Time, Undergraduate Students	32	B

Making the Diagram Technique Operational

In each of the four settings, I was introduced to the class by the instructor. The instructor explained to the class that I was a graduate student doing research for my dissertation in the field of diagrams and prior knowledge. After the introduction, I described the diagram technique to the students. They would use paper and crayons to help them create diagrams. They would be constructing diagrams in response to each of three questions. I explained that they would have five minutes to complete each diagram. The time required to facilitate the technique included distributing the materials to the students. Facilitating the exercise took me approximately 30 minutes with the smaller class, and 40 minutes with the larger classes. The remaining time was set aside to give students an opportunity to describe their diagrams to their fellow students. The last five minutes of the facilitation exercise was reserved for concluding remarks by the instructor. We agreed in advance that the facilitation would be limited to one hour of classroom time in each of the four classroom settings.

I observed the students assisting one another in distributing the crayons and paper with a degree of excitement and curiosity. This was likely due to the novelty of the exercise. The literature review did not surface research related to student diagrams used to elicit prior knowledge. I expected few if any students to have previous experience creating diagrams of prior knowledge. I also believe that the energy level I observed in the classroom was related to their prior experience using crayons in elementary school or earlier. Crayons introduced an element of fun and playfulness.

I did not observe any hesitancy in the students as they prepared for the exercise. I explained the steps that they were to follow in answering the questions. The answers would be in the form of a diagram. The diagrams were to contain only triangles, squares, and circles. I emphasized that letters, numbers, words, arrows, special characters, or other symbols were not allowed in the diagrams.

I pointed to my watch and noted that each question would be timed. I told them in advance that they could volunteer to explain their diagrams to the class, if time permitted. I did not receive any clarifying questions from the students prior to the start of the exercise. The instructors sat near the front of the class in each of the four settings and observed the exercise. The instructors did not participate in the diagramming technique.

My experience and observations noted similar behaviors of the students in the four classroom settings. The students participated in distributing the materials at the beginning of the exercise. They also assisted in collecting the diagrams and materials at the end of the exercise. During the diagram exercise, I observed the students creating diagrams without any discussion among themselves, although the instructions did not restrict this communication. Students' behavior seemed to indicate that they did not want to share the diagrams before the end of the diagramming part of the exercise. I believe the phrasing of the questions had the effect of recommending a quiet and serious demeanor, and waiting to share the diagrams until the end of the time was up for all three questions. For each question, I observed that some students started diagramming immediately. Other students would think about the question and hesitate before beginning to create a diagram. Some of the students seemed to diagram as if the goal was to finish first and other students would continue diagramming right up until the instruction was given to stop. This behavior was similar across all four classroom settings.

At the end of the facilitations, I explained to the students that they created three diagrams that were intended to represent their prior knowledge of the general concepts prompted by the questions. I pointed out that the diagrams were different and illustrated, in a visual diagram, the externalization of their internal mental models. I explained that we carry with us internal mental models of concepts about a domain of knowledge when we experience the real world (Craik, 1967). I explained that the use of the three geometric shapes made the diagrams more abstract (Novick, Hurley, & Francis, 1999). This made it easier to spot differences in the diagrams quickly and without a significant investment in time. I also explained that this form of communicating with diagrams made it easier to contrast and compare how individuals think about concepts (Landy & Goldstone, 2007).

The concept behind the exercise was the idea that teams should make time to explore their conceptual differences when they first come together (van den Bossche, Gijselaers, Segers, Woltjer, & Kirschner, 2011). The differences in individual diagrams helped explain why differences of opinion exist in groups of people. I explained to the students that describing prior knowledge using essays would require a significant investment in time on the part of the instructor and that it is easier to recognize patterns and differences in diagrams. In this respect, diagrams have an advantage over text when recognizing differences in geometric shapes.

Making Prior Knowledge Visually Accessible

The second part of the research question continued with the phrase "and thereby make prior knowledge of the students accessible visually within the context of a domain-specific classroom setting?" The domain setting was varied by conducting the elicitation in each of the four classrooms. The use of three *how*-type questions was designed to elicit the student's prior knowledge of concepts linked to the topic of the class. In contrast to asking declarative (*what*-type) or procedural (*when*-type) questions, the three *how*-type questions guided the students in using geometric shapes in a way that made spatial relations (topology) easy to recognize. This had the effect of replicating the findings described in the Larkin and Simon (1987) research. Differences were easy to see in the diagrams.

Larkin and Simon (1987) made the case that a line, segment, and point contained in a diagram are easier for the brain to locate in a plane due to the spatial indexes. The additional cognitive tasks required for search and inferences are higher when using text. In the elicitation technique, the shapes are spatial representations of concepts located in a plane. The relations between shapes communicate the relations between concepts.

At the completion of the diagram exercises, to further illustrate the differences for the students, I asked for volunteers to explain to their fellow classmates what their diagrams were meant to communicate. There was time remaining for volunteers to explain their diagrams in each class. The students did not hesitate to explain what their diagrams were meant to convey about their prior knowledge of the topic. I also think their willingness to share their explanations was based on the fact that there were no reference diagrams to act as exemplars of good diagrams. The design of the diagram technique was to encourage free and open communication and expression. The use of crayons and basic geometric shapes helped to create this climate of the exercise being an ungraded activity for the class.

The use of crayons and blank paper in combination with the steps outlined in the elicitation technique caused the students to transform internal conceptualizations of prior knowledge into external representations in the form of a spatial topology rendered using geometric shapes. Using diagrams in this manner made it possible to show how conceptual knowledge can be made external in a visual way. The diagrams were accessible visually to the students and instructor.

Engaging a student's prior knowledge of concepts is important, and can be made part of the instructional design of a course using basic materials and the diagram technique. The exercise did, in fact, make the students' prior knowledge visible to them and to the instructor, based on the comments made by the students, and later confirmed in discussions with the instructors. However, the technique did not allow for an evaluation of the *depth* of that prior knowledge or how it connected to other domains that might have been relevant to the class or the instructors. This is an area that will require further investigation in future studies.

Construct Validity

Construct validity generally refers to the validity of the evidence collected and intended to support the interpretations of a particular construct, in this case the diagrams as a valid measure of conceptual differences. Diagrams allow for the direct observation of the dimensions of the concepts created by the students in the diagrams (Salkind, 2010). In this study, the dimensions are characterized as the binary relations of a topology (Egenhofer, 1991). The quality of the elicitation technique rests on a set of measures that are well-defined and establish a clear chain of evidence, thereby reducing the subjective nature of the data collection tasks. The elicitation technique was designed to make it possible to visually recognize differences in conceptual prior knowledge when viewed through the lens of student diagrams. These pattern differences were made more specific and visible using labels to identify the binary topological relations Egenhofer (1991). The topological relations provide the reader with a vocabulary with which to distinguish the differences noted in the student diagrams. The use of the binary relations does not suggest that an algorithm has been identified and used to compute a measure or score for an individual diagram.

The diagrams were marked with anonymous numbers and characters created by the students to aid in grouping the diagrams later for analysis. The diagrams were converted to digital data formats using software that created scanned images stored in a portable document format. Sample diagrams are included in the appendix. The process of collecting, marking, and storing the diagrams constituted the chain of custody procedures. These steps helped to improve the construct validity and quality of the research design.

Internal Validity

Internal validity refers to the causal relationship between the diagram created by the student and existence of recognizable difference between the shapes placed on the diagram. The binary relations serve the purpose of providing a qualitative lens for describing the differences (Salkind, 2010). The spatial arrangement of the lines, segments, and points in the diagram help the viewer recognize the patterns quickly as being triangles, squares, or circles. Larkin and Simon (1987) set the background for describing differences in pattern recognition using diagrams in problem solving settings. In this case study, the differences in spatial arrangements are set against the background of students generating diagrams of prior knowledge. The diagrams contained topological differences that were easy to detect visually. The geometric shape rules helped to make the diagrams appear more abstract. This made detecting pattern differences easier. The eight binary relations described by Egenhofer (1991) provide a second level of specification by allowing the shape relations to be organized by eight binary relations. The binary relations provided a simple pattern-matching framework and strengthened the internal validity of the study. The differences in patterns are recognizable within and across student diagrams and class settings.

External Validity

Generalizing results to a broader group of people in the university community speaks to nature of establishing the external validity of the diagram technique (Salkind, 2010). This study tested external validity (i.e., determining whether the diagram elicitation technique can be generalized across domain settings) by conducting the facilitation in four different university settings, each with different topics, and involving students with a diversity of experiences and backgrounds. The same framework, technique, and process were used in all four classroom settings. Similar diagrams were generated by the students. The general outcome of the technique was characterized by the diagrams consistently being different in their topologies, but containing some or all of the binary relations, in various configurations. In this respect, the diagram technique, if used widely across a university campus in many different classroom settings, will likely produce similar results. Those results would be in the form of diagrams representing variations in the prior knowledge of concepts by the students in the classroom. The diagram elicitation technique described in this study appears to be generalizable across different classroom settings and topic domains.

Reliability

The final test of the research quality and the elicitation technique was the determination that another researcher, conducting the diagram elicitation technique as it is described in this study, would experience a similar outcome and therefore demonstrate its reliability. To illustrate this test, this case study included the facilitation of the elicitations in four different classroom settings. The goal was to show how the technique reliably produces similar outcomes. The same materials were used in the four settings and similar elicitation question templates were used in the four classes. The elicitation steps were made operational and the instructors served as unofficial auditors of the technique. The students generated diagrams without any intervention on the part of the facilitator or instructors.

The research design improved the outcomes of the tests for validity and reliability. The goal was to make the technique operational in a general way, but applicable for use in specific domains. The combination of the research by Larkin and Simon (1987) with the topology relations described by Egenhofer (1991) strengthened the validity and reliability of the study and the diagram technique.

The reliability of the diagram elicitation technique rests on two fundamental skills and experience that students bring with them to the classroom. First, students are exposed to drawing at an early age in most cases, but there may be exceptions. Drawing geometric shapes is a skill that is included in many subject areas beginning in the earlier grade levels. Triangles, squares, and circles are geometries that appear in most instructional materials, even in the most basic of visual metaphors. Shapes are images that surface in most subject areas long before the student reaches college. Given that the elicitation technique places few constraints on the quality, quantity, configuration, composition, or relations between shapes in the rules, the technique is representative of a combinatorial mix that is likely to generate unique diagrams in most cases. In effect, the variability in the inputs has the likelihood of producing variations in the output, making the technique reliable in this respect.

Research Question Two

The first research question sought to illustrate how a diagram technique could be made general and facilitate the generation of student-generated diagrams in different classroom settings, making prior knowledge visible to the instructor and viewer. The second research question included additional activities organized around the collaboration and sharing of diagrams among the students.

How can the diagrams offer learners the opportunity to collaborate and share diagrams that could lead to the creation of shared prior knowledge?

The time required to elicit the diagrams for question one took a full hour. There was not an opportunity to add an additional hour to the class schedule to accommodate the collaboration and sharing activities. The lack of time in the elicitation to facilitate the creation of shared diagrams led to the design of an alternative approach to data analysis of potential student collaboration.

A Framework for Collaboration

The diagrams contained within them a pattern of relations that are known as the basic eight binary, topological relations. These relations are recognized internationally as the standard for describing geometric topologies (Kresse & Danko, 2012). The student diagrams contained shape differences and relations that were visually differentiated between students, by question, and by classroom setting.

Student diagrams have embedded in them hidden patterns of binary relations that are not self-describing to the casual observer, yet have significant meaning to an expert in diagram and geospatial topology. The framing of the second research question was to position the resulting student diagrams as informal research artifacts that could then be used by the class for further activities that could be classified as collaborative in nature.

The objective of this study was not to make the instructor an expert in the cognitive science of topology. The analysis of the diagram differences can be characterized within the framework of the eight binary relations that topology experts have established as the foundational differences that can exist between two shapes that co-exist in a plane. The diagram technique had the effect of translating shapes to place holders for concepts and the binary relations as the way of characterizing and categorizing concepts in a domain of study.

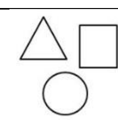
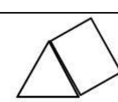
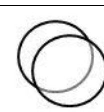
This creates a framework within which the instructor can create collaboration exercises for students. These activities would guide students in how they explore the differences in their conceptual understanding within a domain of study. The sample questions described in the next section illustrate how general questions can serve as a foundation for adaptation to specific domains.

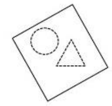
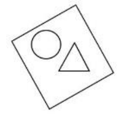
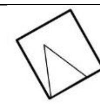
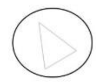
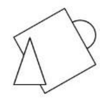
Student Collaboration Using Conceptual Relations

The student diagrams offer the instructor a ready-made corpus of diagrams for engaging the students in small group exercises and the creation of shared conceptual diagrams—and connecting to prior research and conceptualization about the concept of diagramming. Egenhofer (1991) described eight binary relations of topology that are used as the standard in the geospatial community when describing differences represented in spatial diagrams. Each binary relation can be re-written for use in interpreting the spatial relations depicted between the shapes in the student diagrams. This translation of spatial relations into more meaningful collaboration questions is depicted in Table 4.2. This is a significant contribution to the field of educational psychology. The proposition that abstract conceptual diagrams can be translated into the construct of a spatial topology suggests a link exists between what the mind records in memory and how it is replayed in the form of student-generated, external diagrams.

Table 4.2

Conceptual Relations

Relation	Collaboration Question	Visual Example
Disjoint	What are the attributes and values that make concepts distinct in this domain?	
Meet	What are the attributes and values that connect these concepts along a common boundary in this domain?	
Equal	What are the attributes and values of concepts that are viewed to be equal to each other in this domain?	

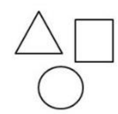
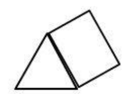
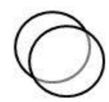
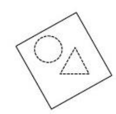
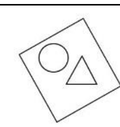
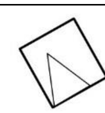
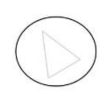
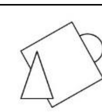
Relation	Collaboration Question	Visual Example
Inside	What are the attributes and values of concepts that are contained within a larger encompassing concept?	
Covered By	What are the attributes and values of concepts that are covered by and replaced by other concepts that are present in the same space?	
Contains	What are the attributes and values of concepts contained within another concept and share a common boundary with other external spaces?	
Covers	What are the attributes and values of a concept that obscure and hide another concept from view?	
Overlap	What are the attributes and values of a concept that overlaps part of another concept, hiding part of it from view?	

The Role of Topology in Student Collaboration

Topology is a branch of mathematics that is concerned with the study of geometries and sets of shapes. By definition, any placement of a line, segment, and point on a blank canvas is eligible for study through the lens of topology. The elicitation technique includes instructions that ask students to draw geometric shapes. The placement of the very first line, segment and point by the student qualifies the diagram as having a topology, no matter how primitive (Mendelson, 1962). The diagram elicitation technique is designed in a way to restrict the student to only drawing diagrams, making it much easier to recognize the relations between the shapes as defined by Egenhofer (1991). The use of the questions in the technique to elicit student knowledge of concepts has the effect of the topology representing the relations between concepts.

One of the facilitations was conducted in a graduate school class whose topic for the semester was the theory and practice of college teaching. Their diagrams are topological representations of concepts in the field of college teaching. The appendix contains examples of the diagrams from these students. The relations between concepts to be explored in the college teaching domain were re-written as an example in Table 4.3. This exercise is an example of how the binary relations can used to frame questions that promote further discussions of the diagram shapes and meaning.

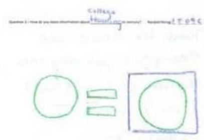
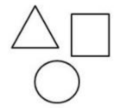
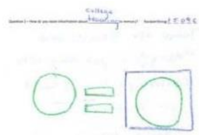
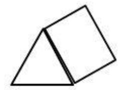
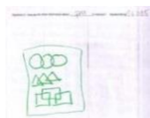
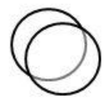
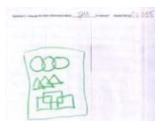
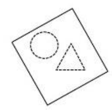
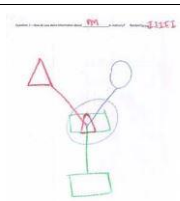
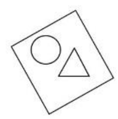
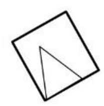
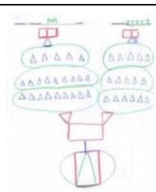
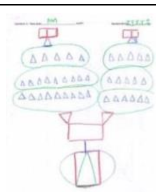
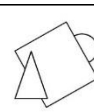
Table 4.3
Conceptual Relations of College Teaching

Relation	Collaboration Question	Visual Example
Disjoint	What concepts make up the domain of college teaching?	
Meet	Do the concepts in college teaching share common attributes and values?	
Equal	Are there concepts in college teaching that have similar meaning?	
Inside	Is there a hierarchy of concepts that can be inferred in the field of college teaching?	
Covered By	Are there concepts in college teaching that can replace other less significant concepts in use and practice?	
Contains	Are there concepts in college teaching that can be organized within the boundary of a larger concept?	
Covers	What concepts might hide the meaning of less visible concepts in college teaching?	
Overlap	Are there concepts in college teaching that overlap meanings found in other concepts?	

The diagram examples in Table 4.4 show the similarities between the binary relations in student diagrams and their labels as described in the work by Egenhofer (1991).

Table 4.4

Student Examples of Conceptual Relations in College Teaching

Relation	Student Diagram	Visual Example
Disjoint		
Meet		
Equal		
Inside		
Covered By		
Contains		
Covers		
Overlap		

My research and analysis suggests that the topological binary relations may serve as general framework facilitating student collaboration and the creation of shared knowledge. This hypothesis was formed without the opportunity to collect data in the form of student responses to domain-specific topology questions. I estimated that such an effort would take several hours of class time and would require a significant investment in time by the instructor.

Research Question Three

The research design included a proposed activity to interact with the instructors several weeks after the elicitation exercises and solicit their feedback regarding their observations and experience with the elicitation technique in their classes. The research question designed to frame this topic is provided below.

To what extent does the instructor perceive the diagram technique to be useful as a tool for eliciting prior knowledge at the individual level, and at the group level?

The goal was to determine to what extent the instructors perceived the diagram technique to be useful as a tool for eliciting prior knowledge at the individual level and at the group level. The data collection and initial follow-up inquiries with the instructors surfaced a change in the communications and dynamics that followed over the subsequent weeks with the instructors.

Instructor Experience Using Diagrams

During the initial discussion with the instructors regarding their willingness to sponsor the diagram elicitation technique, the concept of using diagrams to illustrate differences in how students conceptualized prior knowledge in a domain seemed an innocent enough arrangement and they agreed to participate. One instructor agreed to host the facilitation in a graduate class on the topic of college teaching. The other instructor was an adjunct professor teaching at two different universities. This instructor agreed to sponsor the other three elicitation exercises in a combination of undergraduate and graduate school classes.

The concept of using diagrams in the classroom was not new to the instructors. They did mention that the use of abstract diagrams constrained by rules that only allowed triangles, squares, and circles was a new idea for them. I explained my experience with the technique in the original format as it was facilitated in a graduate school class in 2009, and how the materials and technique were changed to accommodate a larger class size with minimal investment time or materials.

The instructors also acknowledged that their students came to class with a broad range of backgrounds, education, and cultural upbringing. We discussed how the use of diagrams in the exercise appeared to be effective in my 2009 class project. I described for the instructors how the diagrams were a useful technique for encouraging students to express visually how they think the real world works. I explained how the analysis of the student diagrams indicated that nothing more than basic skills, knowledge, and ability to use crayons were required to produce abstract diagrams of conceptual knowledge. The instructors were supportive of using a technique that only required blank paper and crayons.

Instructor Behavior Observing Students

The instructors did not participate in the elicitation exercises. They took a seat in the classroom and watched their students create the diagrams. Neither instructor was familiar with the work of Larkin and Simon (1987) or Egenhofer (1991). One instructor had an academic background in educational psychology, but was unfamiliar with research related to the nature of diagram use in the classroom. The other instructor had a background in business and information technology. The concept of using abstract diagrams to elicit prior knowledge was new information for both instructors. This did not surprise me as I had found few sources in my literature review that related to eliciting prior knowledge using student-generated diagrams.

At the conclusion of the elicitation exercises the instructors summarized for their students the value of using diagrams to help visualize how people see the world through different perspectives. There were several questions during the elicitations in which a student asked what the shapes were meant to communicate. I made the point that the diagrams are valuable in how easily they communicate differences.

Instructor Responses to Interview Questions

The original plan, based on the IRB application, was to interview the instructors, and record, transcribe, and code the interviews. The instructors chose to opt out of this interview process—an option provided to them and included in the IRB agreement. They both expressed to me in conversations after the diagram experience that they did not want to participate in any type of interview other than being willing to answer a series of questions that were sent to them in advance.

The use of diagrams as a formal instructional tool is not taught in the educational community based on the literature reviewed for this study. In particular, diagram use in this study is narrowly focused on a very specific definition of a diagram, one that is abstract in rendering, and only allows for the inclusion of three geometric shapes. The use of diagrams in this study is also oriented to the elicitation of knowledge that is conceptual in nature. This study does not explore the use of diagrams that are concrete in representation, or address knowledge that is considered declarative or procedural in nature.

In my professional practice, designing and constructing conceptual models of information architectures for government and commercial clients, the use of diagrams is often unfamiliar to the teams I support. I have observed professionals in the workplace reacting to the diagram exercise in ways very similar to the behavior of the students. The behavior is a mix of curiosity and speculation. I believe the instructors find the use of diagrams a challenge without guidance and instruction. The instructors told me that diagram training is not offered as part of their education and training. I believe the experience for the instructors of not being able to explain the meaning of the diagrams to their students is a significant obstacle to wider adoption of diagram use in the classroom. I felt responsible for not estimating in advance how much more time should have been allocated to exploring the use of diagrams in the classroom, and believe the diagram elicitation has limited use without introducing instructors to the research of Larkin, Simon, and Egenhofer.

The concept of data permeates our culture. Data comes in all types of digital shapes and sizes (text, images, pictures, graphics, video, audio, messages, web pages, and maps). Abstract diagrams represent another type of data, but a type not commonly known outside the fields of cognitive science and psychology. Data are often referred to as schemata in these fields. A schema is an outline of an object or event that is experienced by human beings in the real world. Schema theory suggests that our experiences are stored in more abstract schemas in memory to improve storage and retrieval (Mandler, 1984). It appeared that the students and instructors sensed that there was more to the diagrams than was discussed in the elicitation exercise.

Speculating on what this meaning could be was not a topic that could be easily integrated into the class during the elicitation exercises. This underlying lack of experience and knowledge of diagrams may have contributed to the instructor's unwillingness to participate in the follow-up interviews.

I was able to reach an alternative strategy with the adjunct instructor responsible for sponsoring the diagram elicitation exercises in three of the four classes. I created a set of questions. The instructor agreed to answer these questions in writing. These answers are provided in appendix. The highlights of the answers are consistent with my observations made earlier.

- The instructor and students found the exercise interesting, but unusual.
- The idea that the diagrams had no right or wrong answer was a limiting feature of the technique.
- The use of the diagrams to build team collaboration was viewed as a valuable feature that should be explored in future research.
- The technique could be improved with the addition of an exercise to create a common vocabulary of concepts.
- The students showed little experience with diagramming as a skill. The instructor stated that the use of diagrams as a communication tool might be a useful addition to the curriculum.

Summary of Analysis

The data analysis in this chapter covered the operation of the diagram technique, how the students might potentially use the diagrams to collaborate and share prior knowledge, and the limitations of the techniques identified through questions and answers provided by one of the instructors. Combining the work of Larkin and Simon (1987) with the topology of Egenhofer (1991) helped give structure to the data analysis and illustrate how diagrams can be used in an educational setting.

The use of the diagram elicitation technique to generate abstract conceptual diagrams produced visual data that varied widely. The nature of the data suggested that diagrams are an effective technique for eliciting more personal and ontological representations of student worldviews. The variations in the diagram topology suggested that the underlying foundation of prior knowledge varies in a way that can be engaged quickly with the use of abstract diagrams. The data also suggested that neither the students nor the instructors had prior knowledge of abstract diagram elicitation techniques. The inherent patterns of prior knowledge hidden beneath the surface of the diagrams can be expressed in general topological terms using binary relations. The structure and schemas of prior knowledge and student conceptualizations of domain knowledge are visible in diagrams created with basic paper and colored crayons.

The research design and the technique were used to explore an observed shared behavior among the student diagram constructions. The diagrams shared the feature of being different. The validity and reliability of the technique was established by repeating the process in four separate classrooms using the same instructions and materials. The data also suggested that the challenge of expanding the use of diagrams in the classroom begins once the diagramming elicitation technique ends. The students were limited in the amount of time that had to create the diagrams in this case study. There was not the additional time available for the instructor to facilitate the development of shared student diagrams and the creation of conceptual vocabularies of the subject domain. A summary of the data analysis in the context of the study and recommendations for future research are provided in Chapter Five.

CHAPTER FIVE - SUMMARY, LIMITATIONS, AND RECOMMENDATIONS

My study described the background, literature, diagram technique, and analysis of the data collected from students in the form of diagrams. The diagrams were intended to represent a conceptualization of the student's prior knowledge. The analysis of the diagrams was performed in the context of shapes containing a general pattern of eight possible binary, topological features. I used this approach to illustrate that shapes could be used to categorize the similarities and differences of the student's conceptualizations of prior knowledge. I wrote this study to show how a general diagram technique could be operationalized and applied to the context of prior knowledge in specific domains. Constructivist theories of learning provided me the conceptual framework within which observations about the technique could be situated. This chapter summarizes the case study. Limitations and recommendations for future research are included.

Summary of the Study

The goal of this study was to explore the use of a diagramming technique as a way of eliciting prior knowledge from students in a university classroom setting. I was able to facilitate the technique in four classrooms and observe the students creating abstract diagrams. The diagram technique served as a constructivist learning tool. Research supports the need to engage the student's prior knowledge as an instructional strategy for creating a solid foundation for new learning. The data collected in the form of diagrams supported my goal of visually illustrating that student prior knowledge varies widely.

This study was based on research by Larkin and Simon (1987) that described how diagrams afforded the viewer an advantage over using text when communicating information. Their study led to Egenhofer's (1991) discovery of how binary relations can be used to describe the differences in the diagrammatic shapes. The literature review also uncovered a significant analysis of diagram research from 2000 to 2012 by (Purchase, 2014). The result was a strong body of evidence suggesting that abstract diagram research is a gap in the current diagram research literature. The technique described in this study has the potential to close this gap by offering a general tool for collecting diagram data across many subject domains.

The diagrams collected during the class project led me to the proposition that the seemingly random shapes might contain hidden patterns. The comment by Larkin and Simon (1987), regarding the importance of topology in diagram research, led to the findings by Egenhofer (1991) whose work is seminal in the field of geography. He framed relations between two shapes represented in a diagram as being organized into eight binary relations. The relation between any two shapes in a diagram could be one or several of these relations. These relations provided a way of thinking about concepts in a qualitative way. The relations also provided the framework for describing diagram differences in a structured way.

I observed the reactions of the instructors as they watched their students create diagrams. The instructors did not participate in the diagram exercise. My observations of the students and the instructors led me to the conclusion that diagramming skills are not taught in the university system in any formal way that I could discern. I was successful in answering the research questions outlined in this study and turn to those topics in the next section.

Discussion of the Findings

My research was based on the use of abstract diagrams. This approach led to several insights about the nature of abstract diagram use in the classroom. First, by operationalizing the abstract diagram technique with basic materials and the use of basic shape rules, it was clear from my observations that abstract diagramming as a skill was not a technique familiar to the students or instructors. Despite this situation, the students easily engaged in the technique, and the instructors readily supported my facilitation of the technique in their classrooms. The technique was easy for the students to learn and use. I interpreted this behavior as an indication that the students could conceive of prior knowledge about the class topic and express it in the form of a diagram.

The limited rule set used in the technique allowed them to freely express very different conceptualizations without any questions regarding the nature of there being a right or wrong answer. I made the assumption that the students considered any and all diagrams to be valid and appropriate representations in the context of the class exercise. The diversity of the shapes and relations indicated a broad spectrum of personal interpretations by the students of concepts related to the class subject. This rather simple technique operated as a powerful visual metaphor in a way that made it easy to see the diversity of prior knowledge that students brought with them to the classroom.

I also discovered that the diagrams can be used in ways that consume far more time than I had allocated for the technique in the classrooms. My original research design included an additional task of developing a set of terms to accompany the diagrams. In actuality, the diagramming activity took the majority of the class time that was allocated for the diagram exercise. Only a few minutes remained for some students to share their verbal explanations of their diagrams. The amount of time required to create shared vocabularies was well beyond the time allocated in my study.

An unanticipated finding of the study was the use of topology and binary relations to describe what were thought to be random shape configurations included in the diagrams. The diversity of shapes was a qualitative feature of the diagrams as defined by Egenhofer (1991). The diagrams served as a conceptual space in which students could construct visual representations of prior knowledge.

More time is required during practical application if the diagram technique is to be used to create domain concepts, shared vocabularies, and shared diagrams. The diagrams could be modified and updated throughout the semester as a way of visualizing conceptual change throughout the semester as the students construct new knowledge. This was also an unanticipated finding since conceptual change research is not well understood outside the learning science field (Vosniadou, 2008).

Larkin and Simon (1987) advocated for more rigorous diagram research frameworks. My observations indicated to me that diagrams were an effective communications tool. The need for better tools to communicate information quickly is undeniable in a society driven by technological innovations and rapid change. Abstract diagrams could be useful in communicating information if the research community adopted standard frameworks, tools, and methods.

The hidden topology discovered in the diagrams led me to envision that abstract diagrams could be the basis for the development of novel forms of visual language (Marriott & Meyer, 1998). I interpreted the ease with which the students and instructors engaged with the concept of a diagramming technique as evidence for an underlying spatial intelligence that naturally engages with information (Waller & Nadel, 2013). Research related to diagrams from this cognitive perspective is in the early stages of development (Galantucci, 2010). The study illustrated how diagrams make visible hidden conceptualizations that help human beings visualize prior knowledge.

Limitations of the Study

The gap in the literature related to diagram research in the classroom was specific to the use of abstract external representations that are constrained by geometric shape rules. My case study was designed to address this gap by describing a diagram elicitation technique that was general in orientation, but adaptable to different subject domains.

The technique was not designed to make explicit the meanings and semantics embodied in the diagrams. The study was not designed as a tool for determining how best to produce diagram lexicons, vocabularies, or dictionaries. It was not designed to recommend any particular way of generating abstract reference diagrams that would normally be produced by subject matter experts. The time and resources required to attempt such tasks require a significant investment in time and resources that extend well beyond the context of the classroom setting. The study was not designed to capture and generate harmonized conceptual diagrams within a specific domain of study.

The view of diagrams as data collected in the form of two-dimensional shape artifacts is, by definition, self-limiting. Applying the technique to data with additional dimensions was not within the scope of this study. The diagrams were not used to derive semantics of a person's personal epistemology, social psychology, or mental state of mind. The study situated diagrams within the historical framework of diagram research as a technique that followed in the tradition of a node-link, diagram metaphor. There are other definitions of a diagram that extend beyond the limitations of a *diagram* as defined for use in this study.

Visual perception is fundamental to the human experience. The variation in diagrams along the continuum from concrete to abstract can be explored in unlimited ways given the ingenuity of the human mind. The diagram technique is limited in application by the very nature of its abstractness. This feature was shown to lead to a novel connection between geometric shapes and framing conceptual understanding in the context of binary relations. This is the strongest feature of the technique. The abstract nature allows for great flexibility in adaptation to the world around us. Thinking in diagrams offers a bright future for a new generation of researchers in many domains, inside and outside academia.

Recommendations for Future Research

My search for a standard abstract diagram research framework did not produce any results. I recommend that the diagram technique described in this case study be considered by other researchers for use as a general research framework that can be adapted for domain-specific applications.

I recommend that the diagram technique be used to research new visual languages that adopt different variations of abstract shape grammars in a way that can improve communications in a wide-range of public safety settings. My experience living through the tragic helicopter accident described in the introduction opened my eyes to the value of diagrams as communication tools in all types of industrial safety systems.

I encourage researchers to consider the ways in which diagrams can make explicit, in a visual format, the perceptions of reality that are reflective of both conscious and unconscious cognition. The diagrams can be used as a mental modeling tool to elicit and represent steps in expert problem solving tasks that are known to originate in the unconscious (Kihlstrom, 1987). The nature of abstract diagrams as metaphors for human cognition should encourage researchers to explore how abstract diagrams can be used to improve more subtle aspects of critical thinking, situational awareness, and the unconscious aspects of decision making under pressure. The current research in spatial intelligence is just one example of the renewed interest in visual communications tools, techniques, theories, and practices.

My experience facilitating the diagram technique in four university settings indicated that conceptual change research could likely benefit from the longitudinal use of abstract diagrams as a way of measuring change visually over longer periods of time. Researchers might investigate how abstract diagrams can be used to benchmark and measure the development of cognition and intelligence using abstract diagrams in the university setting.

Researchers in business schools could learn from my experience and develop formal diagram skills courses that expand upon the limited research I used in this study. I only adapted my study based on research from cognitive science, diagram research, and topology. There are likely many other ways to modify and extend abstract diagram skill sets to other domains in businesses across a wide variety of industries.

I encourage researchers to extend diagram research to the lower grades and beyond university settings to vocational schools, trade schools, and technical colleges. The nature of abstract diagrams to communicate information quickly in a way that can be easily understood could have positive impacts on the teaching of behaviors related to public safety and social welfare. Simple iconic diagrams have the potential for improving communications in many aspects of public life. An example of this application could be the development of better diagrams for communicating important information on labels of grocery products, medicines, and toxic chemicals.

My native language is English and my second language in college was German. I believe the intersection of visual language research with spoken language research could lead to expanded vocabularies of international symbol sets across disciplines of shared interest. Visual designs for campaigns advocating for common interests across borders in times of peace and war could benefit from visual languages that operate in times of need.

These are just a few areas where I think the recommendations can be implemented in a short time frame with positive outcomes. Technology is making it possible to capture and communicate data visually with great speed and specificity than ever before. The visual language of abstract diagrams has the potential to illuminate a wide variety research threads beyond those I have mentioned above.

Conclusion

This study was the result of a six year journey that took me on detours into dozens of domain-specific fields of inquiry, science, and the arts. I read widely in the fields of adult learning, human development, anthropology, sociology, computer science, cognitive science, evolutionary biology, computational linguistics, neuroscience, geometry, mathematics, human factors, semiotics, and engineering. The diagram technique I described in this case study resulted in findings that I had not planned on uncovering along the way.

I started this journey with a simple goal. Diagrams used wisely can save lives and prevent senseless human tragedy. Diagrams are a powerful communications tool. My experience of not having planned for adequate time in my own study to conduct all the inquiries is a warning to the adventurous researcher. Diagram research is field that is wide and deep.

I truly have only scratched the surface of research regarding the use of abstract diagrams in the classroom. I do believe the design of the case study and the keep it simple nature of the research questions provides a research framework for other researchers to adapt to their own needs.

Communicating through diagrams is a literacy skill that could begin in the elementary school. The skill should be developed through the years of formal schooling and into adulthood. The simple abstract diagram technique described in this dissertation requires nothing more than the hand and the mind. Paper and crayons are optional. The development and adoption of a visual language is the key to unlocking the landscape of the human mind (Hoffecker, 2011). Draw a diagram, share it with others, collaborate to solve problems, and co-create new knowledge.

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APPENDIX A – IRB APPROVAL LETTER

VirginiaTech

Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120, Virginia Tech
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE: May 28, 2015

TO: Clare Klunk, Arthur Thomas Conroy III

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires April 25, 2018)

PROTOCOL TITLE: Draw Aloud Version 2

IRB NUMBER: **14-014**

Effective May 28, 2015, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the Amendment request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 6,7**
Protocol Approval Date:	**January 10, 2015**
Protocol Expiration Date:	**January 9, 2016**
Continuing Review Due Date*:	**December 26, 2015**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

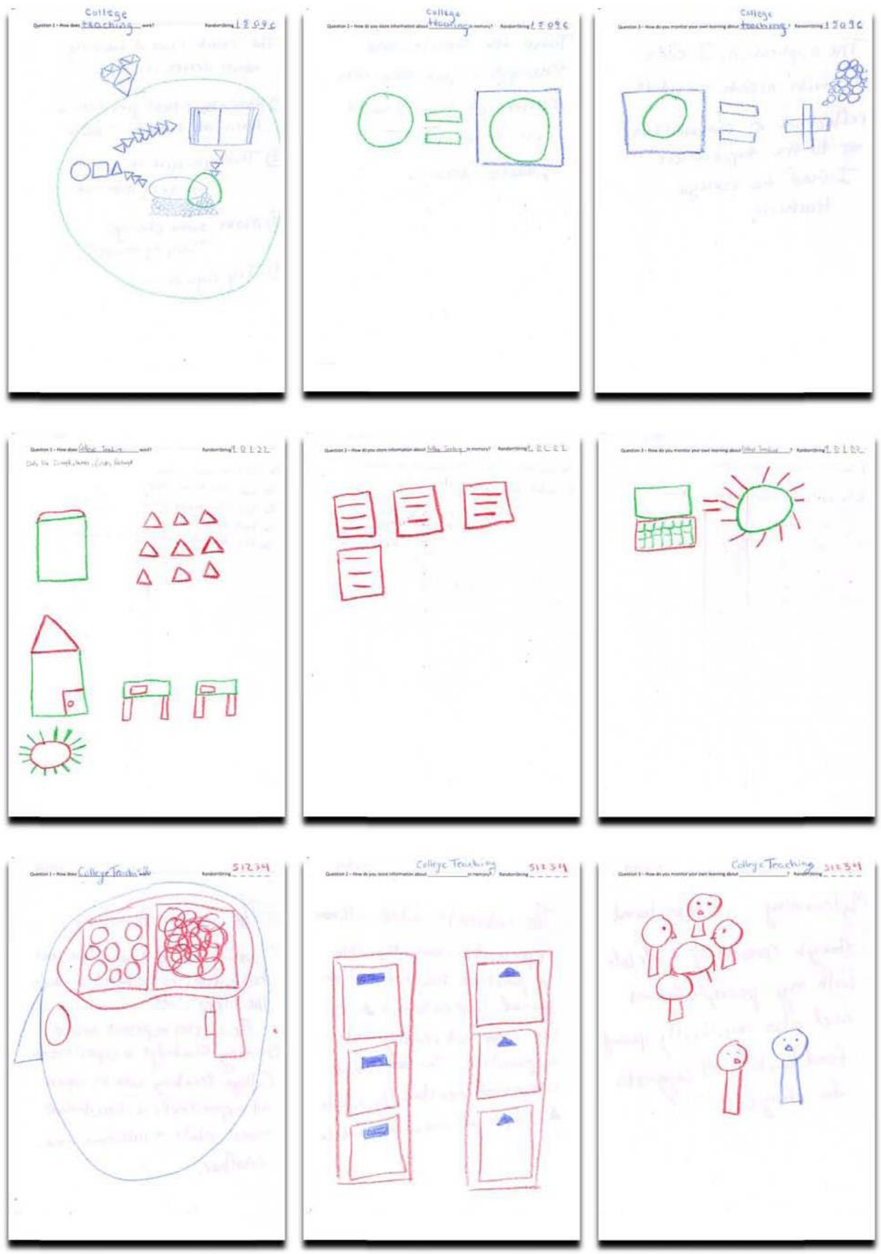
Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

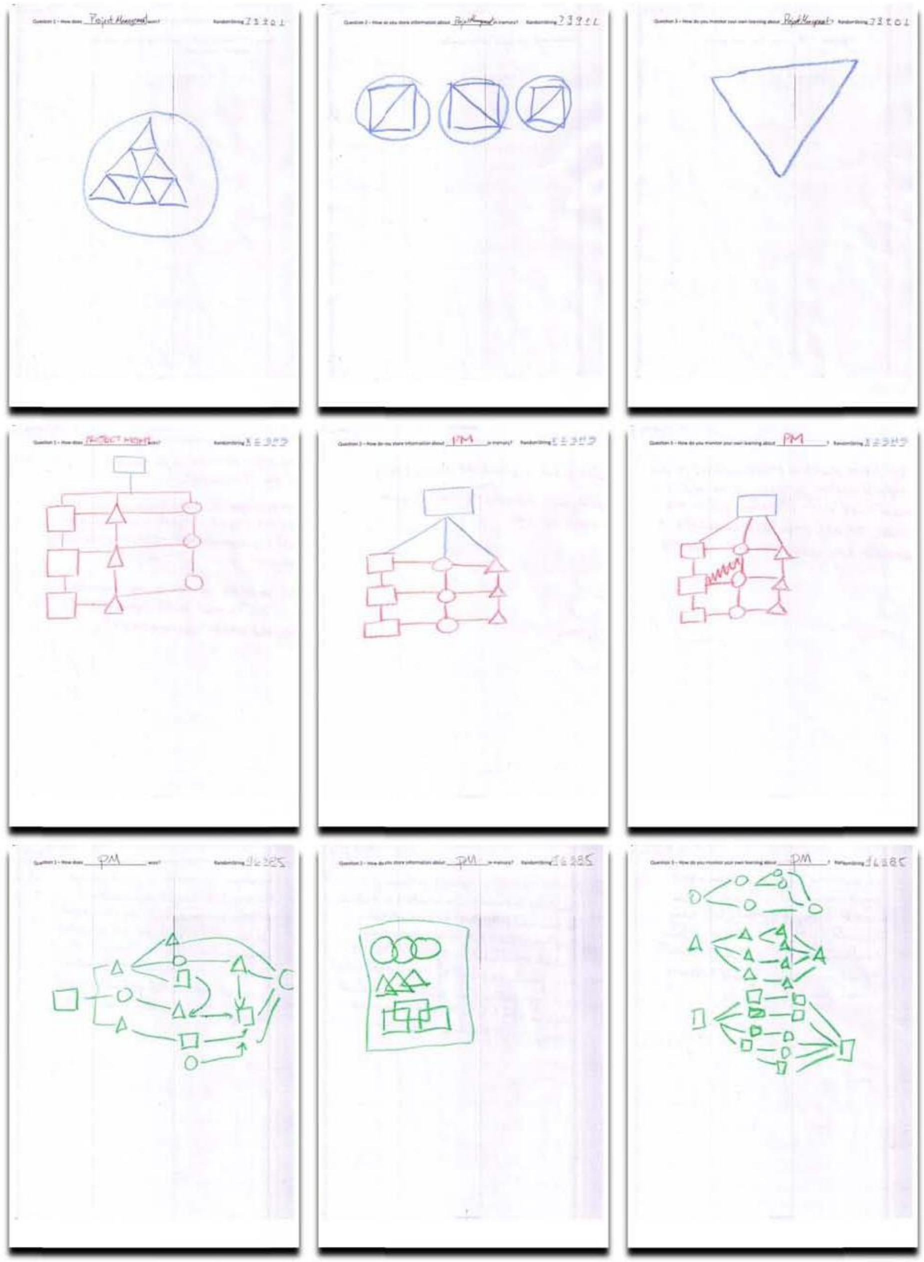
Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

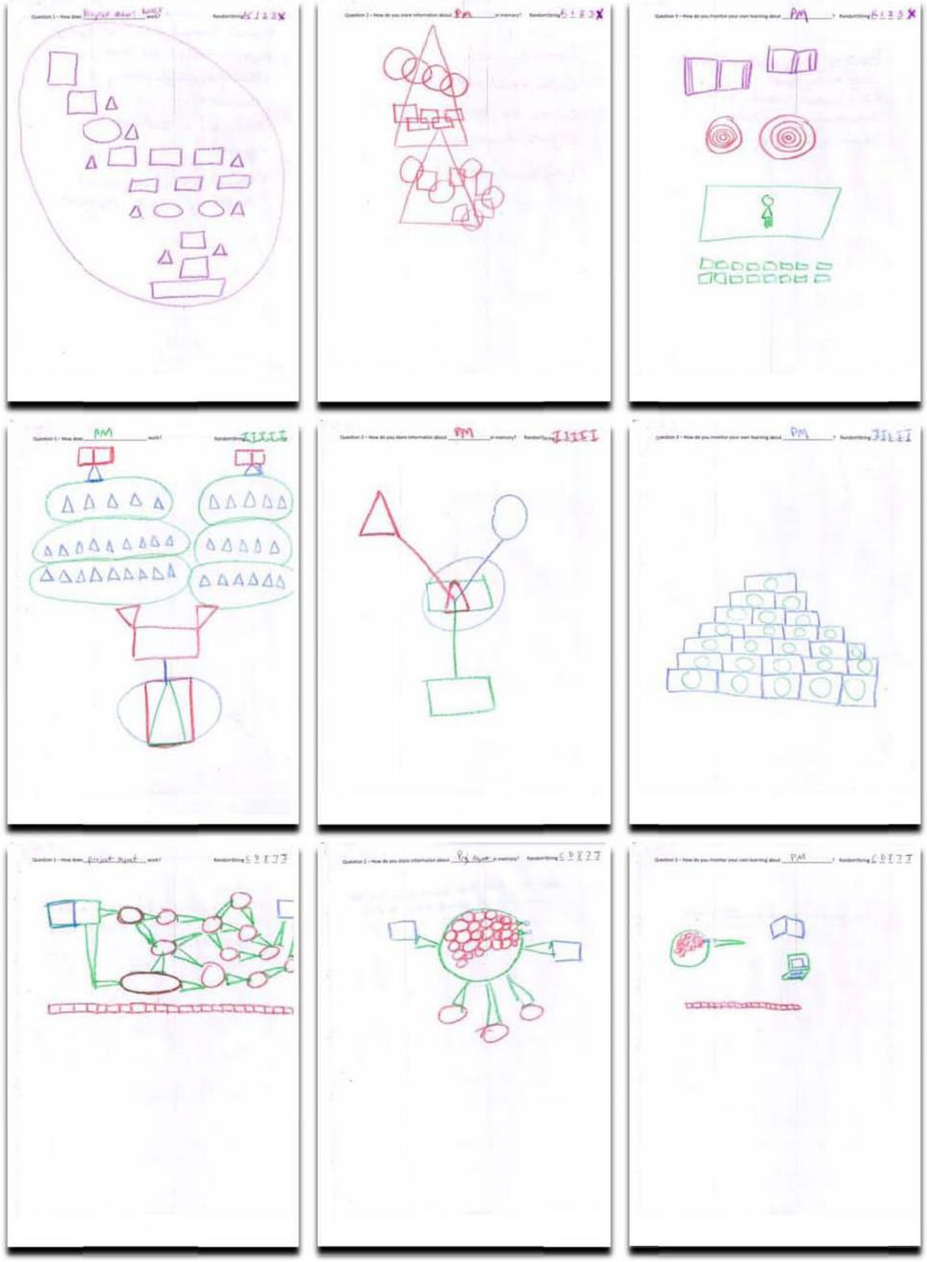
APPENDIX B - SAMPLE DIAGRAMS



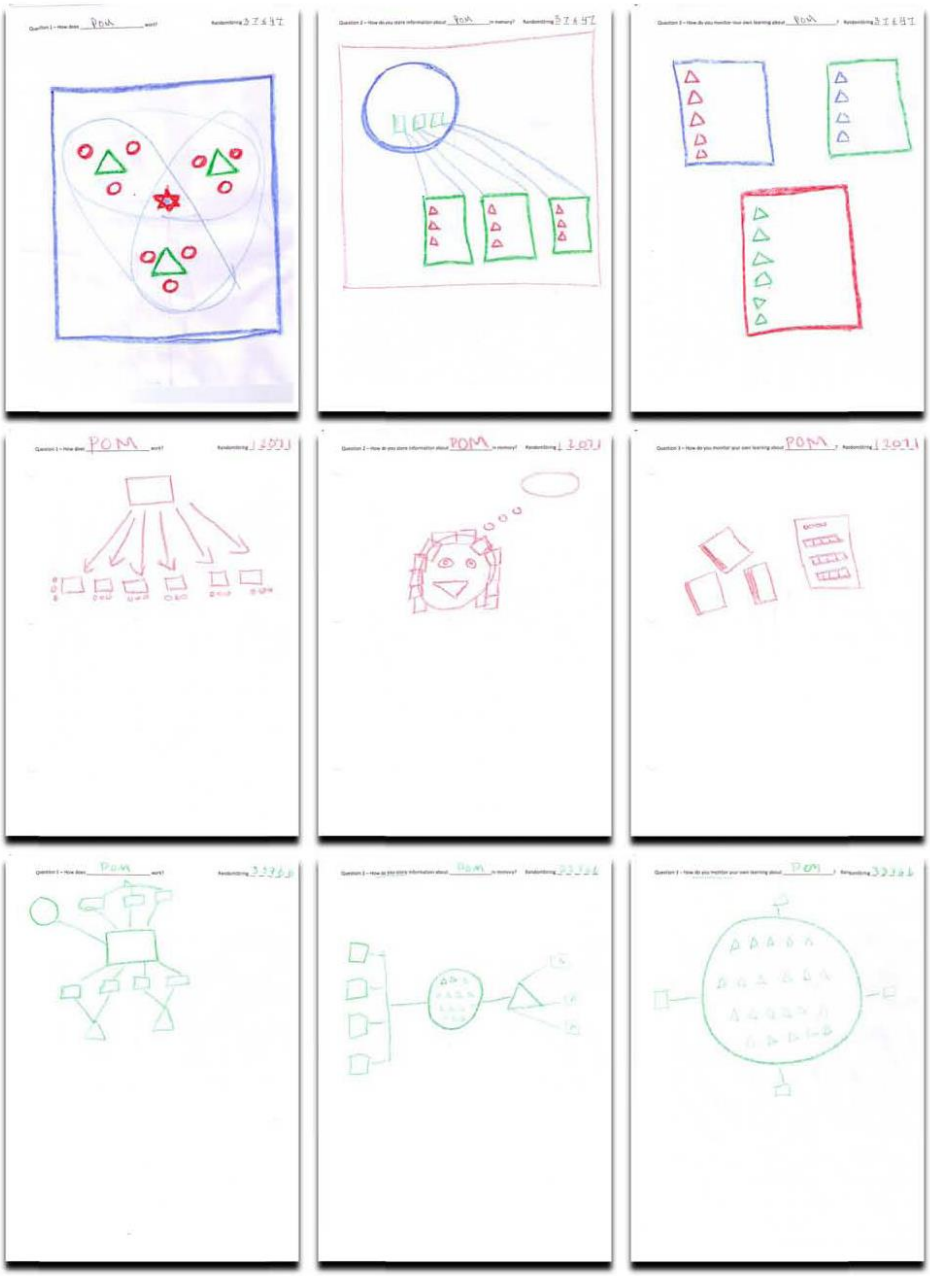
Sample Student Diagrams – Graduate Students, College Teaching



Sample Student Diagrams – Graduate Students, Project Management

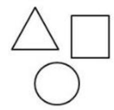
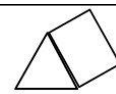
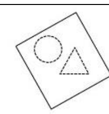
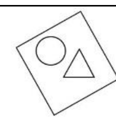
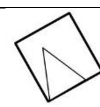
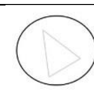
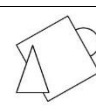


Sample Student Diagrams – Undergraduate Students, Project Management



Sample Student Diagrams – Undergraduate Students, Program and Operations Management

APPENDIX C – CONCEPT TOPOLOGY COLLABORATION QUESTIONS

Relation	**Collaboration Question**	**Visual Example**
Disjoint	What are the attributes and values that make concepts distinct in this domain?	
Meet	What are the attributes and values that connect these concepts along a common boundary in this domain?	
Equal	What are the attributes and values of concepts that are viewed to be equal to each other in this domain?	
Inside	What are the attributes and values of concepts that are contained within a larger encompassing concept?	
Covered By	What are the attributes and values of concepts that are covered by and replaced by other concepts that are present in the same space?	
Contains	What are the attributes and values of concepts contained within another concept and share a common boundary with other external spaces?	
Covers	What are the attributes and values of a concept that obscure and hide another concept from view?	
Overlap	What are the attributes and values of a concept that overlaps part of another concept, hiding part of it from view?	

APPENDIX D – INSTRUCTOR RESPONSE TO RESEARCH QUESTIONS

Question 1

What did you observe regarding the student's response to the diagramming instructions?

>> Both graduate and undergraduate students were initially confused when told they could only diagram using triangles, squares, and circles. At least some thought it was some sort of trick question.

Probe 1A. How did the students react to using crayons and blank sheets of paper?

>> Both graduate and undergraduate students were surprised when asked to draw with crayons and some expressed concern that drawing with crayons was for school children.

Probe 1B. How did the student's react to viewing their own generated diagrams?

>> Both graduate and undergraduate students looked at their own diagrams with a mix of pride and uncertainty. That is, they are often asked questions for which there is only one, correct answer (particularly undergrads) so they could not initially assess if they got it "right" or not.

Probe 1C. How did the students respond to the experience of creating the diagrams?

>> After getting over the initial thought of having to draw with crayons, both graduate and undergraduate students seemed to enjoy the exercise.

Probe 1D. How did the students respond to the use of the three elicitation questions?

>> Most of my graduate and undergraduate students acted confidently that they knew how to diagram how the world works (#1; more of an opinion question) but less so on you store information (#2) and even less so on how you monitor your own learning (#3), the latter two being more technical than opinion.

Probe 1E. What did you observe about the student's response when asked to share their diagram descriptions with the other students in the class?

>> Both graduate and undergraduate students were hesitant to share their diagrams (particularly undergrads, who are used to there being only one correct answer to a question and how can one know if a crayon-drawn diagram is the correct one?). However, once the first few students shared their diagrams it became apparent that no two people diagrammed the questions the same way (or even close to each other) and there wasn't one, "right" answer.

Question 2

What features of the student diagrams did you find aligned with your course content?

>> These exercises were done in a mix of graduate and undergraduate courses in Information Systems (business courses, not computer science ones) and project management. For the IS courses, it fit very well because the underlying course theme was, "Convert data into information so we can solve problems and make better decisions." and students could see the relevance. For project management courses, the alignment was even stronger, particularly when they were asked by Mr. Conroy, "How many of you have ever joined a project team and were asked, 'How do you define how the world works?'" The grad students really resonated with this as the impacts of not having a shared vocabulary were apparent.

Probe 2A. When you review samples of the student diagrams, what meaning would you assign to the different shapes created by the students in their diagrams?

>> The variability was too great to assign a particular meaning to a given shape; however, the question "How does the world work?" elicited the most consistent shape definitions. That is, most answers fell into one of three, main categories using the following shapes:

Power (or hierarchy) = triangle

Structure = square

Love (or symbiosis) = circle

Probe 2B. What meaning would you assign to the differences in shape?

>> Although not measured as part of the exercise, after having watched hundreds of students complete this exercise, I can say anecdotally there were marked differences based on: age, gender, culture, and work experience/area of study.

Probe 2C. What meaning would you assign to the differences in color?

>> None of the exercises done with my students involved an evaluation of color and given the many different crayon colors used I cannot comment on this.

Probe 2D. What meaning would you assign to the differences in size?

>> There was too much variability to comment other than what seemed obvious: the size of the object was related to its strength or importance.

Probe 2E. What did you observe regarding the behavior of the students during their participation in the diagramming exercise?

>> Overall, students found the exercise to be worthwhile and eye-opening when they got to the end and realized diagrams created with crayons and simple shapes can be very useful.

Question 3

What did you observe regarding the technique of limiting the students to using only three geometric shapes when creating their diagrams?

>> Without this restriction, the exercise would have devolved into something resembling interpreting abstract art, with definitions so variable as to make meaningful comparisons nearly impossible.

Probe 3A. What meaning would you assign to the geometric shapes?

>> Hierarchy = triangle

Structure = square

Flexibility (or unity) = circle

Probe 3B. What might be the source of the geometric shape knowledge exhibited by the students?

>> This is difficult to assess objectively. Again, it's anecdotal but there were marked differences based on: age, gender, culture, and work experience/area of study. Perhaps a further area of study would be to control for these variables.

Probe 3C. What meaning would you assign to the differences in shapes exhibited by each of the student's diagrams?

>> See answer to Probe 3C.

Probe 3D. Based on the student diagrams, what would you infer about their prior knowledge of the course knowledge?

>> This is difficult to recall objectively. I can say that there were large differences in prior knowledge. Some students had 10+ years of experience and some were traditional undergrads (19-22 years old). Again, perhaps a further area of study would be to control for these variables.

Probe 3E. What terms would you use to describe the range of diagramming skills exhibited by the students?

>> I would say most students had not done any more than cursory or simplistic diagramming of concepts or business processes.

Question 4

How could the diagrams be used to support the students in generating shared course content knowledge?

>> I think a team exercise to evaluate and attempt to harmonize the diagrams (at least as far as "How does the world work?") could be very useful.

Probe 4A. How do you think sharing the diagrams in small groups would affect communication between students?

>> I think it would be useful and could contribute to teams coming to a realization more quickly that two people can look at the same thing and explain it very differently.

Probe 4B. How might the creation of shared diagrams improve student collaborations during the semester?

>> Again, I think a team exercise to evaluate and attempt to harmonize diagrams could be very useful. To take this thought to the next level, perhaps a taxonomy of views could be created (maybe something similar to Meyers-Briggs).

Probe 4C. What do you think the response would be of the students when asked to create shared diagrams of prior knowledge?

>> While I think this would be really, really interesting and useful, I suspect some students (particularly undergrads) would be overwhelmed by the question.

Probe 4D. How would you create a rubric for evaluating the differences between diagrams created by different groups?

>> This is a very tough question. Either a Meyers-Briggs type rubric or what I have used to explain organizational structures:

Triangles = hierarchies that are organized around function; the fundamental question they ask is, "Who is in charge?"

Squares = matrix companies that are organized around outcome; the fundamental question they ask is, "How can this problem be solved?"

Circles = virtual or Protean companies are organized around tasks; the fundamental question they ask is, "What needs to be done?"

Probe 4E. What type of behaviors would you expect from small groups when collaborating to create shared diagrams?

>> This is another very tough question. I would say the younger the audience, the more structure/definition is needed to prevent the exercise from devolving into an exercise in unsubstantiated opinions.

Question 5

What changes to the diagram technique would you recommend to better formalize the diagramming rules and constraints in a way that it can become a learned skill that the students can use in other settings?

>> While adding formality and structure helps guide teams to a common "language", it may conceal dramatic differences in definitions. If the goal is commonality, the instructor should explain definitions of the shapes, color, and sizes; if the goal is to illustrate the difficulty in getting to commonality, less formality is better.

Probe 5A. How often do you encourage students use diagrams in the classroom?

>> This is highly dependent upon the course. While nearly all the business classes involved a minimum of using diagrams created by other people, most Information Systems classes include basics of business process modeling (BPM) creation. However, if the syllabus doesn't call for diagramming, I don't include it.

Probe 5B. How would you describe the features of the diagramming exercise to a fellow instructor or peer?

>> I would say this is a great icebreaker or tool to help teams learn early on the challenges they will face working together.

Probe 5C. How would you change the diagramming rules to improve the diagramming technique?

>> Again, it depends upon the desired outcome: commonality = more formality; not commonality = less (or no) formality.

Probe 5D. In which domains of study do you think diagrams work best?

>> At a minimum: Information Systems, Project Management, Organizational Development, and Entrepreneurship.

Probe 5E. How would you explain the role of using diagrams in classroom discourse and student communications?

>> Having watched hundreds of students complete this exercise I can safely say that some sort of diagramming skills and/or diagram use should be required in business courses (and I'm not talking about formal diagrams such as Use Cases, ERD, DFD, etc.)

Question 6

How would you change the technique or add additional annotations to the diagrams to strengthen their use as a data collection tool for use by instructors?

>> Perhaps allowing students to add text callouts to shapes to explain their meaning.

Probe 6A. What role do you think text labels could play in the technique?

>> A great idea.

Probe 6B. How would the outcome of having the students create a shared vocabulary impact your approach to the concepts in the course?

>> Again, it depends on the course. Some IS courses and most project management or Organizational Development courses could benefit greatly from a shared vocabulary.

Probe 6C. How would you compare the use of other rule sets, such as concept maps, to create diagrams?

>> It depends upon the course but I can see this being very useful.

Probe 6D. How could the diagrams be used as research data?

>> As was mentioned previously, controlling for factors like: age, gender, culture, etc. could be extremely useful to businesses looking to maximize performance from cross-functional teams. Likewise, assessing how high-performing teams diagram things could yield strong insights into some of the reasons why such teams do so well.

Probe 6E. How would you explain the advantages of the diagram technique to other instructors?

>> I would say something like, "Using this technique, in 30 minutes or less, you will able to gage your students' abilities to collaborate and communicate effectively in teams."

Probe 6F. How would you explain the disadvantages of the diagram technique to other instructors?

>> The level of subjectivity could make-or-break this technique.

Probe 6G. How would you change the technique or add additional annotations to the diagrams to strengthen their use as a data collection tool for use by educational researchers?

>> At a minimum: age, gender, ethnic culture, business culture (e.g., finance, marketing, and engineering), industry, major/concentration, work type (project-based or operations).

Question 7

What other techniques would you recommend for eliciting prior knowledge from the students using external representations that are graphic in nature?

>> Perhaps showing trends in past diagrams (e.g., something like, "X% of people define way world works as X, Y, or Z."

Probe 7A. How could identifying gaps in prior knowledge benefit the instructors?

>> I'm not sure how this would be done – I think there would have to be some way to determine what prior knowledge there should be so that the gaps could be identified. For example, I poll my students before the semester as to their knowledge (on a numeric scale) of certain concepts and software programs. By having a numeric scale, I calculate an average score per skill that I use to determine where the center of the distribution lies. I don't see how triangles, squares, and circles could yield something similar but that may be because I'm thinking more quantitatively.

Probe 7B. Can you recommend other tools and techniques when eliciting prior knowledge of the students about the course domain knowledge?

>> Perhaps a situational or role-playing exercise could be used as a prelude to the diagraming exercise.

Probe 7C. How could identifying gaps in prior knowledge benefit the students?

>> Please see comments on Probe 7A.

Probe 7D. How could identifying gaps in prior knowledge benefit the educational researchers?

>> Again, if the issues in Probe 7A could be overcome/addressed, researchers might be able to tell instructors what to expect from a given group of students regarding their prior knowledge and gaps thereof.

APPENDIX E – INSTRUCTOR RESEARCH QUESTIONS

Question 1

How did you think the students understood the diagramming instructions?

Probe 1A. What was the student's reaction to using crayons and blank sheets of paper?

Probe 1B. What was the student's reaction to viewing their own generated diagrams?

Probe 1C. How would you characterize the student's response to creating the diagrams?

Probe 1D. How would you characterize the student's response to the three questions?

Probe 1E. What did you think about the student's response in sharing their diagram descriptions with the other students in the class?

Question 2

What features of the student diagrams did you find interesting?

Probe 2A. What do you think the differences in shape placement meant?

Probe 2B. What do you think the differences in shape meant?

Probe 2C. What did you think the differences in color meant?

Probe 2D. What do you think the students thought about the differences in their diagrams?

Probe 2E. What did you think the student's thought of the exercise?

Question 3

How effective was the technique of limiting the students to using only geometric shapes?

Probe 3A. What do you think the geometry represented?

Probe 3B. Where do you think the geometric knowledge originates in the mind?

Probe 3C. How would you describe the range of differences in the geometric descriptions?

Probe 3D. What type of prior knowledge do you think the geometry represents?

Probe 3E. How would you describe the diagramming skill level of the students?

Question 4

How would you use the diagrams to support the students in generating shared diagrams created by students in small groups?

Probe 4A. What do you think sharing the diagrams in small groups would do to the communication between students?

Probe 4B. How do you think the diagrams could improve the student's perception of the new material they are learning?

Probe 4C. How involved do you think the students would become in creating shared diagrams?

Probe 4D. How do you think the students would evaluate the shared diagrams created by different groups?

Probe 4E. How would you evaluate the diagrams created in small groups?

Question 5

How would you make changes to the diagram technique to better formalize the rules and constraints in a way that it becomes a learned skill that the students can use in other settings?

Probe 5A. How often do you think the students use diagrams in the classroom?

Probe 5B. How would you describe the features of a diagramming skill?

Probe 5C. How would you change the rules to improve the diagramming technique?

Probe 5D. In which domains of study do you think diagrams work best?

Probe 5E. How would you explain the role of using diagrams in discourse and communication?

Question 6

How would you change the technique or add additional annotations to the diagrams to strengthen their use as a data collection tool for educational researchers?

Probe 6A. What role do you think text labels could play in the technique?

Probe 6B. How would the outcome of having the students create a shared vocabulary impact your approach to the concepts in the course?

Probe 6C. How would you compare the use of other rule sets, such as concept maps, to create diagrams?

Probe 6D. How would you use the diagrams as research data?

Probe 6E. How would you explain the diagram data to other instructors?

APPENDIX F – KEY TERMS

The key terms are defined for the reader in this appendix. The terms are in such general use across domains that they can be easily misinterpreted. The definitions are provided within the context of how they are used in this study and not meant to extend these interpretations or meanings to other research domains.

Diagram is defined within the context of this study as a visual image that is constructed through the physical process of locating a point and a connecting line on a drawing canvas, is this case, a piece of blank paper (Larkin & Simon, 1987).

The diagram is further constrained by the limitation that excludes embellishments, annotations, labels, numbers, and other special notations, making the diagrams *abstract* in contract to *concrete* diagrams (Purchase, 2014).

The node-link, point-line connections must be constructed in such a way as to create the geometric shapes of triangles, squares, or circles. These are the only shapes allowed in the diagram created by the students. This rule or specification is referred to in the literature as a *shape grammar* (Stiny, 1975).

The drawing canvas is embodied in the form of a blank sheet of paper measuring 8.5 by 11 inches. The diagramming utensils are a random collection of colored crayons chosen by the students from a large selection stored in a box. The materials make it possible for students to construct external representations of internal thought processes in a location referred to by cognitive science researchers as a *conceptual space* (Gardenfors, 2000, 2014).

Domain as used in this case study refers to a body of knowledge that is normally identified by a subject label such as physics, economics, biology, and mathematics (Novick, 2006). *Domain-specific* is meant to communicate that a noun or adjective is specific to one domain when compared to other domains. *Domain-general* is meant to communicate or describe a noun or adjective that can be applied across different domains (Novick, 2006).

Knowledge describes the collection of facts, processes, information, data, skills, and abilities associated with a subject area (Sowa, 1984). In turn, it follows that *prior knowledge* is the collective knowledge a student brings with them to the classroom that they have acquired through education, training, and life experience (Dochy et al., 1999). The study adopts the further breakdown of prior knowledge into *declarative*, *procedural,* or *conceptual* types of knowledge (Jonassen, 2006; Jonassen et al., 1993; Jonassen & Strobel, 2006).

Declarative knowledge refers to the collection of facts, statements, and principles that describe a subject or specific domain (Jonassen, 2004).

Procedural knowledge refers to the collection of processes, methods, and activities that describe how to act upon or with facts, statements, principles, or physical objects in a subject or specific domain (Jonassen, 2004).

Conceptual knowledge refers to the collection of symbolic representations, space-time events, and physical things humans experience in life. Similar features shared by concepts and the similar relationships shared between concepts are used to describe classes of symbolic representations, space-time events, and physical things (Jonassen, 2004; Murphy, 2004).

Topology is a mathematical concept that defines a set of points, along with a set of shapes described by the points, and includes a definition of the relations between the shapes in a two-dimensional plane (M. Egenhofer, 1991; Mendelson, 1962).

Binary relations are a categorization of the eight possible topological relationships that can exist between two shapes in a two-dimensional plane. (M. Egenhofer, 1991; M. Egenhofer, 1994).